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PRACTICAL HEAT

TERRELL CROFT, EDITOR

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PRACTICAL HEAT

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Consulting Engineer

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Formerly Associate Editor of Power

Second Edition
Tenth Impression

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PREFACE TO THE SECOND EDITION

As stated in the Preface to the First Edition, this entire work has been planned on the basis of the fact that one cannot really understand the application of heat to power plant work unless one is familiar with the basic fundamentals of the subject. Hence, the first fourteen divisions of this book have been devoted to the theory of heat, presented by the author in simple language and without the use of complicated mathematics. Since the theory of heat as covered in this book has not changed, little revision has been necessary in this part of the book. The remainder of the book deals with the application of these fundamentals to power plants. The art of power plant design has advanced materially since the author's original work; hence these latter divisions needed revising. Mr. Croft was unable to undertake this work and I have been authorized to do it for him.

In revising this book I have endeavored to maintain the author's style and simplicity of language and presentation.

R. B. Purdy.

New York City,
December, 1938.

PREFACE TO THE FIRST EDITION

Practical Heat endeavors to live up to its title. It endeavors to be just what its title indicates. It is a book on heat and the practical applications of heat, which may be intelligently followed by persons of limited mathematical attainments. A working knowledge of arithmetic should suffice. Matters of theoretical interest only have been avoided. While it is emphasized that this is a "practical" book, it should not be inferred that theory has been ignored. On the contrary, the entire work has been planned on the basis of this fact, that one cannot really understand the practical or application features of any subject unless he is familiar with the fundamental theory of the subject.

So, in *Practical Heat* great care has been exercised in the preparation of its earlier divisions to establish firmly these fundamental principles which underlie all heat phenomona. But in establishing these principles the controlling policy has been to present all ideas in such a way that they can be readily understood by those of limited education. While simplicity has been the keynote, technical accuracy has never been sacrificed. Hence, the book should also prove useful to any reader —regardless of the excellence of his previous education—who desires an accurate, easily-assimilated treatment of the subject.

Drawings for all of the illustrations were made especially for this work. It has been the endeavor to design and render these pictures so that they will convey the desired information with a minimum of supplementary discussion.

Throughout the text, principles which are presented are explained with illustrated descriptive expositions or with worked-out arithmetical examples. At the end of each of the 19 divisions there are questions to be answered and, where justified, problems to be solved by the reader. These questions and problems are based on the text matter in the division just preceding. If the reader can answer the questions and

solve the problems, he then must be conversant with the subject matter of the division. Detailed solutions to all of the problems are printed in the appendix in the back of the book.

As to the method of treatment: Force, pressure, work, energy, and power, are first considered because they are fundamental concepts upon which all physical science is founded. Next follows a discussion of the nature of heat, its basic significance, its one source, and its relation to matter and temperature.

Succeeding this, in the division on *Heat—Its Measurement And Transformations*, the fundamental laws of heat phenomena, such as the first law of thermodynamics, the second law of thermodynamics, and the fundamental heat-transfer equation, are expounded in a simple manner. Upon the principles and laws which are stated in this division (and which are more fully developed in the succeeding divisions) are based all practical engineering processes.

The effects of heat, such as the expansion and contraction of solids and liquids, the heat phenomena of gases, the melting and freezing of substances, vaporization, and the properties of vapors, are then examined. In the division on *Heat Phenomena Of Gases* it has been the endeavor to treat this rather theoretical subject so that the practical man—or one with little mathematical training—can readily understand it.

Following this discussion of the effects of heat, gas and vapor cycles are introduced, since the principles involved therein form the groundwork of all practical heat-engine and heat-power-plant design. In the next division the subjects of combustion, fuels, steam power plants, internal-combustion-engine power plants, building warming, and refrigeration are given space, as they are the practical *applications* of heat phenomena. In these "application" divisions the aim has been to demonstrate how the principles which were developed in the preceding divisions are employed in practical heat engineering. Finally, a division on instruments is included. In this are shown the various instruments which are employed in heat engineering; their purposes, usefulness, and limitations are examined.

With this, as with other books which have been prepared by the author, it is the sincere desire to render it of maximum usefulness to the reader. It is the intention to improve the book each time it is revised and to enlarge it as conditions may demand. If these things are to be accomplished most effectively, it is essential that the readers cooperate. This they may do by advising the author of alterations which they feel would be desirable. Future revisions and additions will, insofar as is feasible, be based on such suggestions and criticisms from the readers.

Although the proofs have been read and checked very carefully by a number of persons, it is possible that some undiscovered errors may remain. Readers will confer a decided favor in advising the author of any such.

TERRELL CROFT.

UNIVERSITY CITY,
ST. LOUIS, MO.,
February, 1923.

ACKNOWLEDGMENTS

The editor desires here to acknowledge the assistance which has been rendered by various concerns and individuals in the preparation of this book.

Among the companies which have cooperated are the H. K. Porter Co., Pittsburgh, Pa.; Central Scientific Co., Chicago, Ill.; American Radiator Co.; Harrison Safety Boiler Works; Buck Stove & Range Co., St. Louis, Mo.; Westinghouse Machine Co., East Pittsburgh, Pa.; Vilter Mfg. Co.; Henry Vogt Machine Co.; Taylor Instrument Co., Rochester, N. Y.; Defender Automatic Regulator Co., St. Louis, Mo.

Furthermore, certain of the text material appeared originally as articles in certain trade and technical periodicals, among which are *Power*, *Combustion*, *Southern Engineer*, and *Power Plant Engineering*.

Numerical values for tables and graphs have, in certain instances, been taken from engineering textbooks of recognized high standing. In such cases acknowledgment is made at the place where the values are used.

Special acknowledgment is hereby accorded Edmond Siroky, Head Mechanical Engineer of The Terrell Croft Engineering Company, who has been largely responsible for the technical accuracy of the book, who prepared or supervised the preparation of much of the manuscript, and who has originated and assisted throughout in many valuable ways.

Other acknowledgments have been made in different places in the book. If any has been omitted, it has been through oversight and, if brought to the editor's attention, it will be incorporated in the next edition.

TERRELL CROFT.

CONTENTS

	Page
Preface to the Second Edition	v
Preface to the First Edition	vii
Acknowledgments	xi
DIVISION 1	
Force, Pressure, Work, Energy, Power	1
DIVISION 2	
Matter, Heat, Temperature	35
DIVISION 3	
The Source of Heat	60
DIVISION 4	
Heat—Its Measurement and Transformations	67
DIVISION 5	
Transfer of Heat	97
DIVISION 6	
Effects of Heat	131
DIVISION 7	
Expansion and Contraction of Solids and Liquids	159
DIVISION 8	
Heat Phenomena of Gases	187
DIVISION 9	
Melting and Freezing of Substances	255
DIVISION 10	
Vaporization	269
DIVISION 11	
Steam and Other Vapors	319

Page

DIVISION 12

Gas and Vapor Cycles 375

DIVISION 13

Fuels 417

DIVISION 14

Combustion 439

DIVISION 15

Steam Power Plants 464

DIVISION 16

Internal-combustion-engine Power Plants 513

DIVISION 17

Building Warming 545

DIVISION 18

Refrigeration 605

DIVISION 19

Instruments 649

Solutions to Problems 683

Index 705

PRACTICAL HEAT

DIVISION 1

FORCE, PRESSURE, WORK, ENERGY, POWER

1. Such Terms As "Force," "Work," "Energy," And "Power" Are Discussed At The Outset because an understanding of their technical significance is essential to the intelligent study of heat and its effects. As the reader proceeds, it will be shown that *heat is energy.* Furthermore, *energy is stored work* and *work is force multiplied by distance.* If the student is thoroughly familiar with these ideas he need not, necessarily, read Div. 1. But probably, in any case, a review will be profitable.

2. A "Force" Is A Push Or A Pull; this is the technical meaning of the word force. That is, a force is anything which has a tendency either to impart motion to a body which is at rest, or to change or destroy the uniformity of the motion of a moving body. A force may be due to an attraction or a repulsion. Also, not only may a condition of rest or motion be altered by a force but the body itself may be altered thereby. It may be stretched, compressed, twisted, or bent.

EXAMPLE.—If a force is applied to a stationary body, the body then moves or tends to move. If the body is already in motion, its speed or its direction of motion will be changed by the application of the force. Or, possibly, both its speed and its direction may be changed. The speed may be increased or decreased, depending on whether the force assists or opposes the motion.

EXAMPLE.—The most common force is that due to gravity. It is called weight. If a thing weighs 10 lb., this means that the earth pulls on it with a 10-lb. force. Steam exerts force on an engine piston. Internal steam pressure exerts force on the bolts in a flanged pipe union. The bolts exert a restraining force.

3. The "Pound" Is A Unit For Measuring Force.—A properly calibrated spring balance (Fig. 1) will indicate the magnitude of a force in pounds. Other weighing devices may

sometimes be used to determine the magnitudes of forces. Although units other than the *pound*—such as the "ounce," "gram," "ton" and "kilogram"—can be used for measuring forces, the "pound" is the one which will be employed most often in this book.

Note.—In Practically All Research Work, And Altogether In Europe, Great Britain Excepted, Metric Units Are Used for measuring forces and weights. The *gram* is the metric-system unit of force and weight. The *kilogram*, a larger unit, is 1,000 grams. See Table 4.

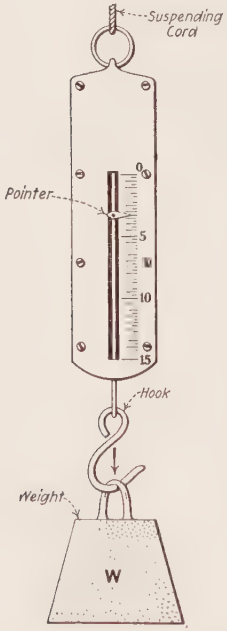


Fig. 1.—Weight is force due to gravity; the spring balance reads 3¼ lb.

Example.—Figure 1 illustrates the force of gravity. Gravity is pulling the weight, **W**, down with a force of 3¼ lb. Opposing the downward pull, the spring in the balance is pulling up with a force of 3¼ lb. Thus here, as always, there are two equal and opposite forces.

Example.—In Fig. 2, the spring balance is measuring pulling forces. Note that there are two opposing 10-lb. forces. One is exerted by each hand. These two forces must be equal and opposite.

Example.—To move a freight car (Fig. 3) along a track, a force, *P*, must be applied. This force, or draw-bar pull, is necessary to overcome the friction of the wheels on the track, that of the axles in the bearings, and the resistances due to wind pressure and inertia. The sum of these opposing forces must be equal and opposite to the draw-bar pull. If, in some manner, the friction be decreased, the force of 625 lb. will be more than sufficient to pull the car at the speed at which it had been traveling. The excess force will then become effective in overcoming the inertia of the car. Thus, the car's speed will be increased until the wind and other resistances become sufficiently great that the 625-lb. draw-bar pull is just counterbalanced by them; then again the car will be drawn along at a constant though greater speed.

Note.—The Difference Between Weight And Mass should be understood. *The mass of a body is that which remains unchanged in all the transformations which the body may undergo. The weight of a body is the gravitational force or pull which is exerted on the body by the earth.* The weight of a body is different at different points on the earth: on a mountain peak its weight will be less than at sea level. Were the body

carried (if possible) to the center of the earth, its weight there would be zero. But its mass is independent of its position. The standard or unit of mass is (in the English system) the *pound mass* which is the amount of mass in a certain lump of metal that is carefully preserved in London. The unit of weight is the *pound force* which is the force required

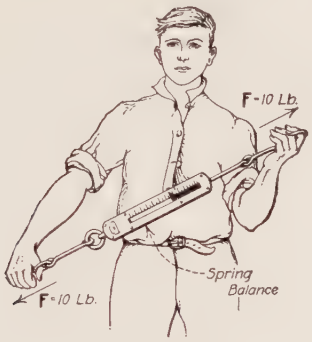


Fig. 2.—Force due to a pull; the spring balance reads 10 lb.

to support the standard pound (mass) body at sea level and 45 deg. latitude. *Weights are indicated by spring balances; masses are indicated by platform balances.* Thus, if a pound mass were supported by a spring balance and carried to different elevations, the balance would show

Fig. 3.—Draw-bar pull (force) on freight car.

different weights for the same substance—if it were carried to the center of the earth it would read zero. But, if a pound mass were balanced on a platform scale against another equal mass, the two masses would balance at all points on or in the earth.

It is a fact, however, that the weight of a body for different places on the earth's surface varies, between the extremes, by only about ½ per cent. Hence, for all practical purposes, it may be assumed that the weight of a body is a measure of its mass. In this book, therefore, no distinction will, in general, be drawn between the mass of a body and its weight. The "pound" will be used to mean both "pound mass" and "pound weight."

4. Table Showing Relation of Metric-system to English-system Units Of Force Or Weight.—The English ton here tabulated is the "short" ton as used in the United States. In Great Britain the "long" ton (2,240 lb.) is used instead.

	Units	English			Metric		
		Ounce	Pound	Ton	Gram	Kilogram	Metric ton
English	1 oz. =	1	$\frac{1}{16} = 0.062,5$	$\frac{1}{32,000} = 0.000,031,25$	28.35	0.028,35	0.000,028
	1 lb. =	16	1	$\frac{1}{2,000} = 0.000,5$	453.6	0.453,6	0.000,454
	1 ton =	32,000	2,000	1	907,200	907.2	0.907,2
Metric	1 gram =	0.035,3	0.002,2	0.000,001,1	1	$\frac{1}{1,000} = 0.001$	$\frac{1}{1,000,000} = 0.000,001$
	1 kilogram	35.27	2.205	0.001,1	1,000	1	$\frac{1}{1,000} = 0.001$
	1 metric ton =	35,273.6	2,204.6	1.102	1,000,000	1,000	1

EXAMPLES.—1 *oz.* = 28.35 *grams.* Also 1 *ton* = 907,200 *grams.* Again, 1 *lb.* = 16 *oz.* = 0.000,5 *ton* = 0.453,6 ***kilograms,*** etc.

5. "Pressure" Is Force Per Unit Area, as the word is used in a technical sense; note that its technical meaning is different from its general meaning. If two substances are in forceful contact, the surface of contact of each substance forces or holds back the contact surface of the other. The *intensity of the force* at any point on the contact surface *is called the pressure.* If two solids (Sec. 50) are pushed against each other with a force and if, Fig. 5, the areas of contact are perfectly smooth plane surfaces, the force between the two solids is assumed to be of equal intensity throughout the entire area of contact. That is, each unit area of the contact surface is assumed to take its share of the total force between the two bodies. The force sustained by each unit area is called the *pressure* of contact. Now when a *fluid* (a liquid or a gas) is confined within a container, it will take the shape of the container—a liquid will contact with the sides and bottom of the container; a gas will contact with all of the interior surfaces of the container. The fluid will then exert a force against the container at every contact point. The intensity of the force at any point is called the pressure at that point.

NOTE.—THE TERM "PRESSURE" IS GENERALLY USED ONLY FOR FLUIDS because it is doubtful whether the intensity of force between solids is ever uniformly distributed over the contact area as was assumed above. There are certain kinds of solids, however, which behave somewhat as do liquids and for which the term pressure is also often used—sand, soil, crushed rock, and similar finely divided substances are examples of such solids.

6. Fluid Pressure At Any Point Is Equal In All Directions.— It is proved in text-books on physics that the same force is exerted upward, downward, or sideways upon a small area which is so moved about within a fluid medium that its center is always at the same point. This may be explained by the perfect freedom of movement of the particles (molecules, Sec. 50) of a fluid among one another. One particle of the fluid exerts the same force on the particles above, to the right, to the left, and (except for its own weight which is so very small) below it. Hence, the fluid pressure at any point is equal in all directions. At different points, however, the fluid pressures may be widely different. At any point the fluid

pressure depends on the height and nature of all fluids which are so situated above that point that they may produce pressure at that point. How fluid pressures are produced is explained below.

Explanation.—Imagine a huge square shaft or stack, *AB* Fig. 4, to extend from the bottom of a deep sea to the height of 60 miles above sea-level. Above this height we may assume that there is no air or atmosphere. Hence, above the plane *A* there is nothing that could press down on the plane *A*. Between plane *A* and plane *C*, however, exist a few particles, let us say, of the lighter gases which compose our atmosphere. These particles are attracted to the earth by gravity. Hence, they push downward on the plane *C*. Therefore, each square inch or other unit area which goes to make up plane *C*, is subject to a force or pressure. Between planes *C* and *D* are more particles than between *A* and *C*—because of the compressibility of gases. Hence, there is a greater downward push on plane *D* than on plane *C*. Therefore, each square inch, say, of plane *D* sustains a greater force than does each square inch of plane *C*—that is, the pressure at *D* is greater than that at *C*. The pressures on like planes below *D* would thus be greater as they are taken nearer to the sea-level. Thus the force acting downward on plane *E* is due to the weight of the gases in *AE*. Likewise at *S* (sea-level), the force pressing downward on the surface of the water would be that due to the total column of atmosphere *AS*. Each unit area of *S* would have to sustain its share of the weight of the gases in *AS*. The variations of atmospheric pressure are given in Sec. 9.

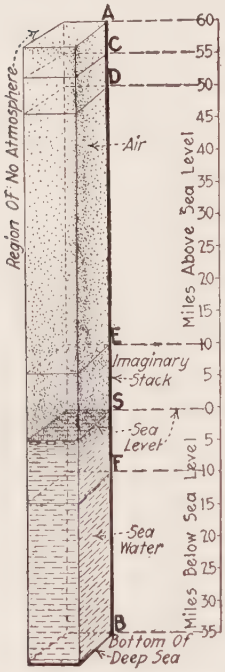


Fig. 4.—Illustrating why fluids exert pressure.

If, now, we consider a plane *F* at some distance below sea level, we find that there is acting down on this plane the weight of the water in *SF* besides the weight of the air in *AS*. The maximum pressure in the column would occur at the bottom plane *B* which is subject to the weight of all water in *SB* together with the weight of all of the air in *AS*.

To summarize, it may be said that *the deeper or higher the fluid column above a point and the greater the density of the fluid, the greater will be the pressure at that point.*

7. The Units In Which Pressures May Be Expressed are many. Since pressure is force per unit area and since forces

may be measured in pounds, tons, and the like and areas may be measured in square inches, square feet, and the like, we have such pressure units as *pounds per square inch, pounds per square foot, tons per square foot,* and others. Furthermore, since any given pressure may be considered as the equivalent of that due to a liquid column of a certain height, it follows that pressures may be expressed in terms of liquid-column height. Hence, we have such pressure units as *inches of mercury column, feet of water column,* and others. The relations of the various pressure units are given in Table 19 and Sec. 18.

8. The Numerical Expression Of A Pressure is, as explained above, obtained by dividing *the total force which produces the pressure* by *the number of area units in the surface* over which the total force is uniformly distributed. This form of expression ordinarily assumes that the force is distributed uniformly over a contact surface. Hence the formula:

$$P = \frac{W}{A} \qquad \text{(pressure)} \tag{1}$$

Wherein: P = the pressure, expressed numerically in the given unit of weight per assumed unit of area. W = the total load or force, expressed in any assumed unit of weight, which is applied to produce the total load or force. A = the total

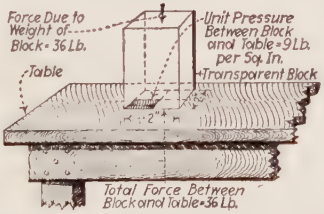

Force Due to Weight of Block = 36 Lb.
Unit Pressure Between Block and Table = 9 Lb. per Sq. In.
Table
Transparent Block
2"
Total Force Between Block and Table = 36 Lb.

FIG. 5.—Illustrating "force" and "pressure" in terms of pounds and square inches.

surface, expressed in any desired unit of area, whereon the total force is uniformly distributed.

NOTE.—If, in For. (1), W = pounds and A = square inches, then P = pounds per square inch. Also, if W = tons and A = square feet, then P = tons per square foot. And so with other combinations of the units of weight and area.

NOTE.—If the total non-uniformly distributed force which is imposed on a surface, is divided by the area of the surface then, the result will be the *average pressure.*

Example.—A certain 36-lb. block (Fig. 5) imposes a load or force of 36 lb. on the area upon which it rests. This area is $2 \times 2 = 4$ *sq. in.* Hence, by For. (1), the average pressure exerted by the block $= P = W/A = 36 \div 4 = 9$ *lb. per sq. in.*

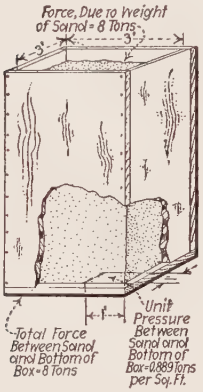


Fig. 6.—Illustrating "force" and "pressure" in terms of tons and square feet.

Example.—A quantity of sand (Fig. 6) is poured into a box which is 3-ft. square inside. Thus the box has a bottom area of $3 \times 3 = 9$ *sq. ft.* The sand weighs 8 tons. Hence, the total load or force which it imposes on the bottom of the box is 8 tons. Then by For. (1), the pressure which the sand imposes $= P = W/A = 8 \div 9 = 0.889$ *ton per sq. ft.*

9. Atmospheric Pressure (Sec. 6) is the pressure which is exerted by the earth's atmosphere. This atmosphere extends for a great, though unmeasured, distance (Fig 7) above and enshrouding the earth's surface. The depth of the earth's atmosphere has been estimated by different experimenters; the estimates range from 30 to 212 miles. This atmospheric pressure varies, according to the altitude, above sea-level,

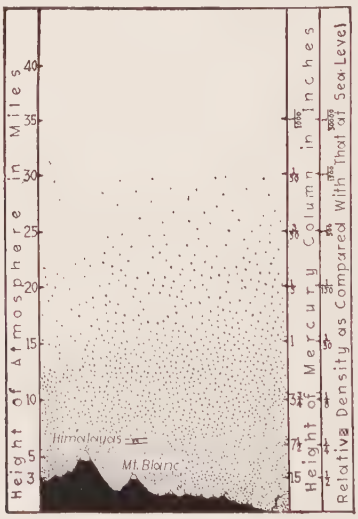


Fig. 7.—Showing how atmospheric pressure decreases as the height above the earth increases.

of the place at which the pressure is measured. At sea-level the atmospheric pressure at a temperature of 32° F. is, so tests

show, about 14.7 lb. per sq. in. That is, *a column of air, which has a cross-sectional area of* 1 *sq. in. and which extends from sea-level to the upper limit of the earth's atmosphere, weighs* 14.7 *lb.*, or more exactly 14.696 *lb.* Thus we are (at sea-level) existing with a pressure of 14.7 lb. per sq. in. which is imposed by the fluid in which we live on all portions of our bodies. The same pressure is imposed on all things which are about us. But we are, ordinarily, unaware of the existence of this imposed pressure in the same way that a fish is, probably, unaware of the existence of the water in which it lives.

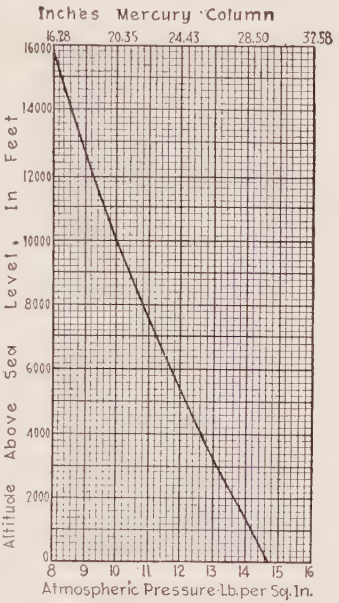


FIG. 8.—Variation of atmospheric pressure with altitude. (Due to the compressibility of air, the pressure does not decrease directly with the height above the sea-level. Hence the graph is not a straight line.)

NOTE.—THE DECREASE OF ATMOSPHERIC PRESSURE WITH INCREASE IN ALTITUDE (Fig. 8) is due to the fact that the depth of the atmosphere above an observer grows less as his altitude grows greater. The atmospheric depth above a man in an airplane 2 miles above sea-level is 2 miles less than the atmospheric depth above a man standing on the ground at sea-level. The man at sea-level is under the pressure—14.7 lb. per sq. in.—due to the full depth of the atmosphere. The man in the airplane is relieved of the pressure due to the 2-mile depth of atmosphere beneath him and therefore (Fig. 8) the atmospheric pressure imposed on him is only about 9.6 lb. per sq. in.

10. Atmospheric Pressure Can Be Measured With A Barometer (Figs. 9 and 10). The barometer is an instrument which operates upon the principle (Fig. 11) of equilibrium between the weight of a column of mercury and the weight of a column of atmospheric air (Fig. 4) of the same cross-sectional area. Pressure which is read on a barometer is called *barometric pressure or barometer reading.*

Explanation.—A glass or porcelain dish (Fig. 12) contains a quantity of mercury, *M*. A 3-ft. (or longer) glass tube, closed at one end and having an inside diameter of any size, is filled with mercury. The thumb (Fig. 12-*I*) is held over the open end of the tube. The tube is then inverted. The open end of the tube, still covered by the thumb, is now thrust beneath the surface of the mercury in the dish. The thumb is then removed. With the tube held vertically, the column of mercury therein will now fall away from the closed end. The

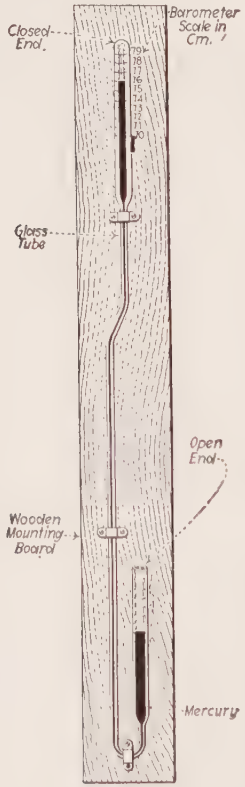


Fig. 9.

Fig. 9.—Simple mercury barometer.

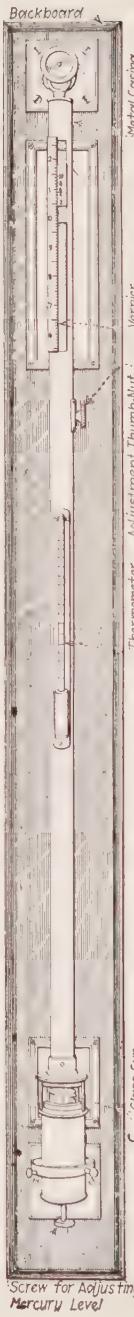


Fig. 10.—Laboratory barometer (for every observation, the level of the mercury in cup *C* must be adjusted accurately to the tip of an ivory point, within *C*, which is not shown).

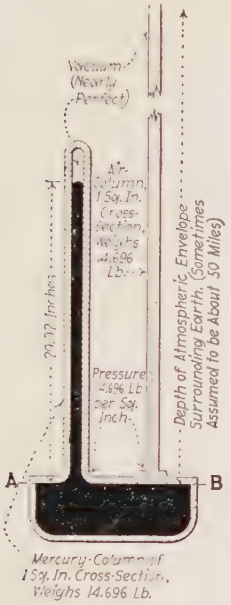

Vacuum (Nearly Perfect)
Air-Column, 1 Sq. In. Cross-Section, Weighs 14.696 Lb.
29.92 Inches
Pressure 14.696 Lb. per Sq. Inch
Depth of Atmospheric Envelope Surrounding Earth, (Sometimes Assumed to be About 50 Miles)
A
B
Mercury Column of 1 Sq. In. Cross-Section, Weighs 14.696 Lb.

FIG. 11.—Equilibrium between column of atmospheric air and column of mercury of equal cross-section.

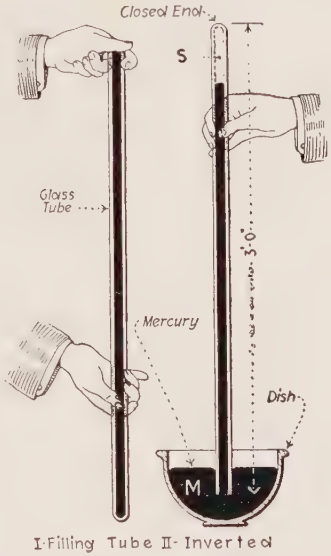


FIG. 12.—How a barometer may be made.

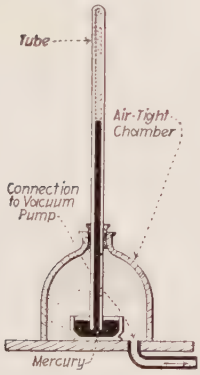


FIG. 13.—Height of mercury column decreases when air pressure is lowered.

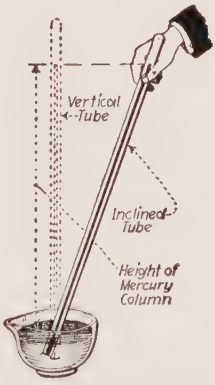


FIG. 14.—Mercury-column height remains the same for vertical or inclined tube.

space, *S*, above the falling column will be a practically perfect vacuum because there is no gas above the mercury. Hence the pressure on top of the mercury column will be practically zero.

But the pressure beneath the mercury column, at its base on the line *AB* (Fig. 11) will be the pressure of the atmosphere. If the experiment is made at sea-level, when the temperature of the air is 32° F., this pressure will (Fig. 11) be 14.696 lb. per sq. in. Therefore, the mercury-column will fall until, due to its height (weight), it will also exert a pressure of 14.696 lb. per sq. in. This condition of equilibrium will be attained when the mercury column falls to a height of 29.92 in. The nominal height of the barometer mercury-column at sea-level is usually taken as 30 in.

If the experiment is made at a point two miles above sea-level, the atmospheric pressure (Fig. 8), due to the 2-mile diminution in the depth of the atmosphere, will be about 9.6 lb. per sq. in. Equilibrium will then be established when the mercury-column falls to a height of 19.55 in.

If the mercury vessel of a barometer, constructed as above specified, be arranged in an airtight closed chamber with the mercury tube extending out of the top (Fig. 13) and the air be partially exhausted from the chamber, the mercury column will fall just as it would if the barometer were carried to a higher elevation. With a perfect vacuum in the chamber, the top of the mercury in the tube will be at the same level as that in the dish. When the dish is exposed to atmospheric pressure, however, the *vertical* height of the mercury column remains the same (Fig. 14) whether the tube is inclined or vertical.

11. The Aneroid Barometer (Fig. 15), since it is much more portable and less liable to derangement, is often used for measuring atmospheric pressures, instead of the mercurial barometer. This instrument may be so accurately constructed as to indicate a difference of elevation of 2 or 3 ft.

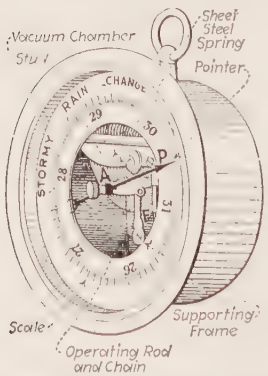


FIG. 15.—Aneroid barometer.

EXPLANATION.—The corrugated top (Fig. 15) of the airtight cylindrical box, *A*, in which there is a partial vacuum, deflects slightly under changes in atmospheric pressure. This motion is transmitted, by a delicate lever system, *F*, to the pointer, *P*. The scale is graduated to read in equivalent inches of mercury column. In general, a *low barometer* indicates stormy weather, and a ***high barometer*** fair weather. Hence, barometer readings may be of assistance in predicting weather conditions.

12. Pressure Gages Are Instruments For Measuring Pressures (Figs. 16 and 22). Perhaps the simplest form of pressure gage is that shown in Fig. 16. This gage indicates the true (absolute, Sec. 15) pressure within the connected vessel. As is explained below, practically all commercial pressure gages indicate the pressure difference between the actual pressure which is being measured and the atmospheric pressure.

EXPLANATION.—The gage illustrated in Fig. 16 is constructed in exactly the same manner as is a mercurial barometer (Sec. 10). Hence, it measures the pressure in a connected vessel exactly as does a barometer measure atmospheric pressure. If the pipe, P, is left open to the atmosphere the gage will measure the atmospheric pressure. If P is connected to a vessel wherein the pressure is less than that of the atmosphere, the mercury will stand at a lesser height in tube T than it would when P is open to the atmosphere. Likewise, if P is connected to a vessel wherein the pressure is greater than atmospheric, the mercury will rise higher in T. Hence, *the height of the mercury column in T is a measure of the pressure in P.*

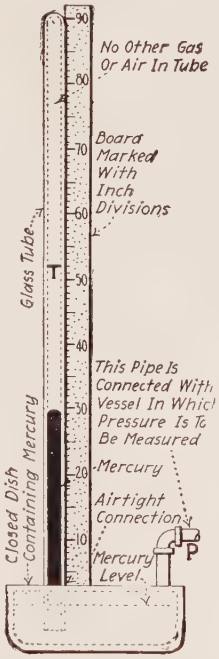


FIG. 16.—A simple form of pressure gage. (As stated in the text, pressure gages similar to this one are not commonly used, because more practical gages can be made. See Div. 19 on instruments.)

Unfortunately, the customary power-plant pressures could only be measured with such a gage as is shown in Fig. 16 by employing tubes, T, of lengths ranging from 20 to 60 ft. Hence, such gages are not commonly employed. Furthermore, for many purposes, the true pressure within a vessel is not as useful as is the pressure difference between the pressure in the vessel and that of the atmosphere. Therefore, gages, Fig. 18, which indicate how much above or below atmospheric pressure a given pressure is, are universally used. NOTE.—For a further treatment of pressure gages see Div. 19 on INSTRUMENTS.

13. The Mercurial Manometer May Be Used For Indicating Pressures Above Atmospheric Pressure (Fig. 17). In the early days of steam-power, gages for indicating boiler pressure were made in this form. With such gages the difference, in inches, in height between the mercury levels in the legs of the

U-tube indicates, in inches of mercury column, the pressure above atmospheric pressure, in the vessel to which the instrument is connected. The operating principle of the mercurial

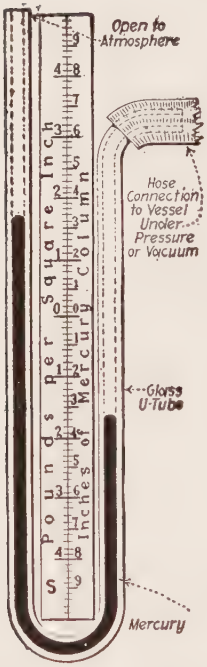


FIG. 17.—Mercury gage for measuring pressures above or below atmospheric. (The scale, *S*, shows that in *mercury column* readings are almost exactly $2 \times$ *lb. per sq. in.* readings; actually 1 lb. per sq. in. = 2.036 in. mercury column.

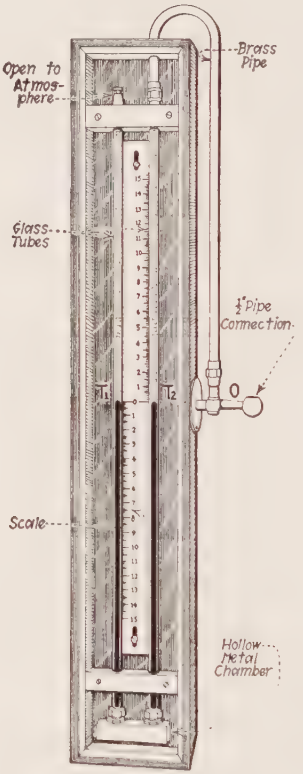


FIG. 18.—Mercurial power-plant vacuum gage. (Although this is called a vacuum gage, it can also be used for measuring small pressures greater than atmospheric. When the pressure in the chamber to which *O* connects is less than atmospheric, the mercury ascends in T_2 and descends in T_1 and vice versa.)

manometer renders the instrument inconvenient, however, for indicating gage pressures higher than about 10 lb. per sq. in.; for higher pressures the tubes would have to be too long.

Note.—Mercurial Manometers Are Commonly Used In Power Plants For Indicating Degrees Of Vacuum (Sec. 16) which are produced in closed vessels. Instruments (Fig. 18) used for this purpose are frequently called *vacuum gages*. With such instruments the difference in the heights of the mercury columns, in legs T_1 and T_2, is an indication of the amount by which the external atmospheric pressure exceeds the absolute pressure within the vessel to which the instrument is attached.

Note.—Manometers For Measuring Very Small Pressure Differences Contain Water Instead Of Mercury.—Since mercury is

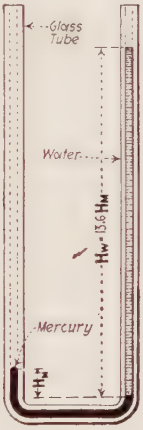


Fig. 19.—A column of mercury supports a column of water 13.6 times as high.

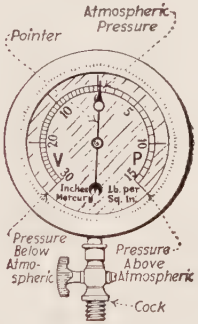


Fig. 20.—Combination pressure-and-vacuum gage.

(Fig. 19) 13.6 times as heavy as water, a column of water having an approximate height of $13.6 \times 30 = 408$ *in.* is required (Sec. 10) to balance the pressure of the atmosphere. Hence, very slight pressure differences, which might not visibly affect the height of a mercury column, would produce quite observable variations in the height of a water column.

14. Compound Pressure-and-vacuum Gages (Fig. 20) are employed in steam power plants. They operate on the same general principle as the Bourdon-tube steam gages which are discussed in Sec. 677. In the illustration the scale to the right, P, gives pressure readings. That to the left, V, gives vacuum readings.

15. The "Absolute" Pressure existing at any point in a fluid medium is understood to mean the true total pressure

at that point—the term "absolute" being used to distingu from "gage" pressure, which is defined in the follow section. The absolute pressure may be (although it seld is) measured with a gage like that of Fig. 16. The m customary method of determining absolute pressure is measuring both the atmospheric pressu (with a barometer, Sec. 10) and the "gag pressure. Since "gage pressure" indicat only the pressure above atmospheric pre sure and since "absolute pressure" is *t total* pressure, it is evident that:

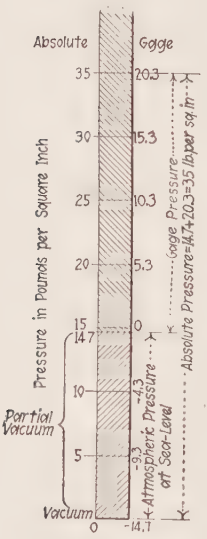


FIG. 21.—Relation between gage and absolute pressures.

(2) *Absolute pressure* = (*Atmospheric pre sure*) + (*gage pressure*)

A negative gage pressure, when adde results in an absolute pressure which less than the atmospheric pressure, as explained in the following examples; s also Fig. 21.

EXAMPLE.—If a boiler contains steam at 1 lb. per sq. in. gage pressure, as shown by the pr sure gage on the boiler, and if the atmosphe pressure at that location and time is 14.5 lb. p sq. in., then the *absolute pressure within the boi* = 100 + 14.5 = 114.5 *lb. per sq. in. absol (abs.).*

EXAMPLE.—If the vacuum gage attached to condenser reads 26 in. of mercury column and the barometer (nearb reads 29.5 in. of mercury column, the *absolute pressure within the conden* = 29.5 − 26 = 3.5 *in. of mercury column absolute.*

16. The "Gage" Pressure existing at any point in a flu medium is understood to mean the difference between t true (absolute, Sec. 15) pressure at that point and the pressu of the surrounding atmosphere. That is:

(3) *Gage pressure* = (*Absolute pressure*) − (*Atmospher pressur*

It is the pressure which is indicated by all commerci pressure gages, such as are shown in Figs. 17, 18, and 2 When such a gage is (Fig. 22) subject only to atmospher

pressure it shows no pressure or, as is sometimes said, "it reads *zero.*" Hence, "*zero gage pressure*" *means* "*atmospheric pressure*"—14.7 lb. per sq. in. at sea level. Whenever such a gage is connected to a vessel wherein the pressure exceeds atmospheric pressure (Fig. 23) the gage indicates a *positive gage pressure,* which is generally called simply a "gage pressure." If the gage is connected to a vessel wherein the pressure is less than atmospheric, it tends to indicate and will if designed therefor indicate a *negative gage pressure,* or simply a

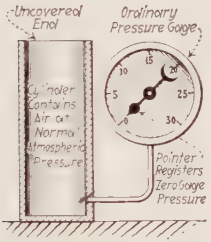

Uncovered End
Ordinary Pressure Gage
Cylinder Contains Air at Normal Atmospheric Pressure
Pointer Registers Zero Gage Pressure

FIG. 22.—Zero gage pressure coincides with normal atmospheric pressure.

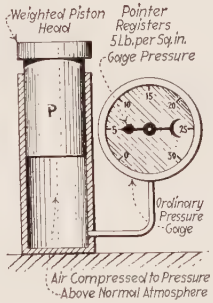

Weighted Piston Head
Pointer Registers 5 Lb. per Sq. in. Gage Pressure
P
Ordinary Pressure Gage
Air Compressed to Pressure Above Normal Atmosphere

FIG. 23.—Gage registers pressure above atmospheric pressure.

vacuum—"vacuum" being understood to mean "partial vacuum." Gages which are used for measuring negative gage pressures are commonly called *vacuum* gages. When compound pressure-and-vacuum gages (Sec. 14) indicate a vacuum, their pointers shift to the other side of the zero mark on the gage scale from the side of the mark on which pressures greater than atmospheric are indicated.

17. Approximate Absolute Pressures In Pounds Per Square Inch May Be Computed From Ordinary Gage-pressure Readings by the following formula. To obtain the exact absolute pressure, the exact atmospheric-pressure value, at the location under consideration, in pounds per square inch must be substituted for the "14.7" value which is shown in the formula.

$$P_A = P_G + 14.7 \qquad \text{(pounds per square inch)} \tag{4}$$

Wherein: P_A = absolute pressure, in pounds per square inch.

P_G = gage pressure, in pounds per square inch. 14.7 = average atmospheric pressure, at sea-level, in pounds per square inch.

Example.—A steam gage connected to a boiler reads 150 lb. per sq. in. What is the approximate absolute pressure within the boiler? Solution. Substitute in For. (4): $P_A = P_G + 14.7 = 150 + 14.7 = 164.7$ *lb. per sq. in. = absolute pressure within the boiler.* However, the stresses in the boiler shell are only those due to a pressure of 150 lb. per sq. in. This is because the surrounding atmosphere presses from the outside against the shell in all directions with a pressure of 14.7 lb. per sq. in.

18. To Reduce Water- And Mercury-column Pressures To Pounds Per Square Inch and Vice Versa, the following equations may be used:

(5) $P = \frac{P_M}{29.92} \times 14.696 = 0.491{,}2P_M$ (pounds per square inch)

(6) $P_M = \frac{P}{0.491{,}2} = 2.036P$ (inches of mercury column)

(7) $P_M = 0.073{,}55P_I$ (inches of mercury column)

(8) $P_I = 13.596P_M$ (inches of water column)

(9) $P_I = 27.684P$ (inches of water column)

(10) $P_F = 2.307P$ (feet of water column)

(11) $P = 0.036{,}13P_I$ (pounds per square inch)

(12) $P = 0.433{,}5P_F$ (pounds per square inch)

Wherein: P = the pressure, in pounds per square inch. P_M = the height of the mercury column, at atmospheric temperature, in inches. P_I = the height of water column, at atmospheric temperature, in inches. P_F = the height of water column, at atmospheric temperature, in feet.

Note.—The Customary Units For Measuring Pressures Are: (1) *Atmospheric pressure and partial vacuums* are generally measured in inches of mercury column. (2) *Gas pressures*, when small, are measured in inches of water column. (3) *Hydraulic pressures* are frequently measured in feet of water column. (4) *Pounds per square inch* is the general engineering unit and is used in nearly all work except that specified above and frequently also for some of the purposes given in (1) to (3).

19. Table Showing Relation Among Units Of Pressure.—The liquid columns are assumed to be measured at normal atmospheric temperature.

Name of unit	Pounds per square inch, P	Pounds per square foot	Inches of mercury column P_M	Inches of water column P_I	Feet of water column P_F
Pound per square inch	1	144	2.037	27.684	2.307
Pound per square foot	0.006,94	1	0.014,1	0.192,2	0.016
Inch of mercury column	0.491,2	70.733	1	13.596	1.136
Inch of water column	0.036,13	5.203	0.073,55	1	0.083,3
Foot of water column	0.433,5	62.424	0.881,9	12	1

EXAMPLES.—*A pressure of* 1 *lb. per sq. in.* = *a pressure of* 144 *lb. per sq. ft. A pressure of* 1 *in. mercury column* = 0.419,2 *lb. per sq. in.*

20. "Work" Is The Overcoming Of Opposition Through Space.—(Note that "work," as the word is used in engineering has a meaning different from its meaning in ordinary conversation.) Work is done when force is overcome through distance. Whenever anything is moved, then work is done. When there is no movement, there is no work. To compute the work done in overcoming force through distance, two factors must be known: (1) *The applied force.* (2) *The distance.* The distance must be measured in the same direction as that of the force.

21. Numercial Expressions Of Work may be obtained by multiplying the applied force by the distance through which the force moves. The force may, in practice, be expressed in any unit of force. The distance may be expressed in any unit of length. The *unit of work* is then formed by multiplying together the given units of force and distance. Hence, the formula:

$$W = FL \qquad \text{(work)} \tag{13}$$

Wherein: W = the work, expressed in the assumed unit-terms of the force and distance. F = the force, expressed in any assumed unit of force. L = the distance, expressed in any assumed unit of length.

NOTE.—If, in For. (13), F = pounds and L = inches, then W = inch-pounds If F = pounds and L = feet, then W = foot-pounds. If F =

tons and L = miles, then W = mile-tons. If F = grams and L = centimeters, then W = gram-centimeters. And so with other combinations of the units of force and length.

22. The Unit Of Work Which Is Used Most Frequently in the United States is the *foot-pound*. A *foot-pound* is the work done when a 1-lb. force is overcome through a distance of 1 ft.

Note.—The Metric Units Of Work Most Frequently Used are, (Table 4) the *gram-centimeter* and *kilogram-meter*. These units are largely employed in South America and in Continental Europe. They are now little used in America.

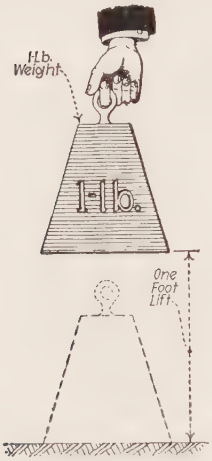


Fig. 24.—One foot-pound of work done against gravity.

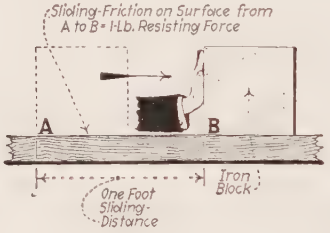


Fig. 25.—One foot-pound of work done against friction.

Example.—A 1-lb. weight (Fig. 24) is lifted vertically to a height of 1 ft. Here the opposing force (Sec. 2) is a gravity-pull of 1 lb. The

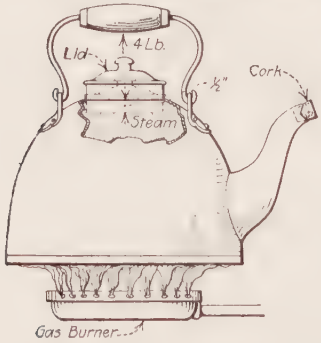


Fig. 26.—Steam in kettle raising lid and thereby doing work.

Fig. 27.—Doing work in lifting a shovel of coal.

distance through which the opposition is overcome is 1 ft. Hence, by For. (13) the work done = $W = FL = 1 \times 1 = 1$ *ft.-lb.* = 1 *unit of work.*

EXAMPLE.—A block of iron (Fig. 25) is pushed through a horizontal distance of 1 ft., along a wood surface. The friction between the iron and the wood develops an opposing force of 1 lb. Hence, by For. (13), the work done $= W = FL = 1 \times 1 = 1$ *ft.-lb.* $= 1$ *unit of work.*

EXAMPLE.—The lid of a kettle (Fig. 26) fits tightly. A total force of 4 lb. is required to lift it. The steam, which is generated in the kettle, pushes the lid upward 0.5 in. What quantity of work is done? SOLUTION.—By For. (13), $W = FL = 4 \times 0.5 = 2$ *in.-lb.*

EXAMPLE.—A man (Fig. 27) lifts a 25-lb. shovel of coal 2 ft. from the floor. Hence, by For. (13), the work which he does $= W = FL = 25 \times 2 = 50$ *ft.-lb.*

EXAMPLE.—A compressed-air hoisting cylinder (Fig. 28) lifts a 125 lb. weight 16 in. Hence, by For. (13), the work done $= W = FL = 125 \times 16 = 2{,}000$ *in.-lb.* $= 2{,}000 \div 12 = 166.5$ *ft.-lb.*

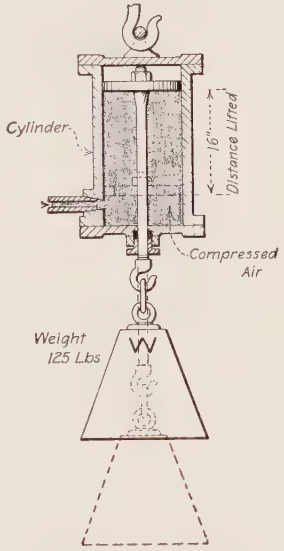


FIG. 28.—Work being done by an air hoist.

23. "Energy" Is Capacity For Doing Work; this is the technical meaning of the word. Energy is ability to do work. It is stored work. Any body or medium which is of itself, due to its position or state, capable of doing work, is said to possess *energy*. Work must, then, have been previously done on the body to change its state or to give it the position whereby it possesses the capacity for doing work. It is impossible to create energy, nor can energy be destroyed. Hence, the amount of energy in the universe is always constant.

NOTE.—ENERGY IS AN ATTRIBUTE OF ALL MATTER.—It is inherent in matter. (Matter is anything which has weight or which occupies space.) This follows (Sec. 3) from the fact that position in space is a property of all matter. Therefore, since matter is (Sec. 39) universal, energy must likewise be universal. Just as there is a definite amount of matter in the universe, so is there a definite amount of energy in the universe. And just as the matter may exist in various aspects, so likewise may the energy exist in various aspects.

24. "Energy" May Be Expressed In The Same Units As Are Used To Express Quantities Of Work (Sec. 22).—This follows from the fact that energy is merely stored work, or

(Sec. 23) capacity for doing work. Thus the *foot-pound* is the commonly-used unit of energy as well as it is of work.

Example.—Energy or work is stored in the ball of Fig. 29. Work was expended in lifting the ball 15 ft. Since the ball weighs 1½ lb., the work done in lifting it from the table top to the position shown is, by For. (13): $W = FL = 1.5 \times 15 = 22.5$ *ft.-lb.* The ball then, with respect to its original position on the table, possesses 22.5 ft.-lb. of energy. Now, if this elevated ball were attached to some machine, such as a clock, and permitted to descend to the table top, 22.5 ft.-lb. of work (neglecting friction) would be given up by and could be realized from it.

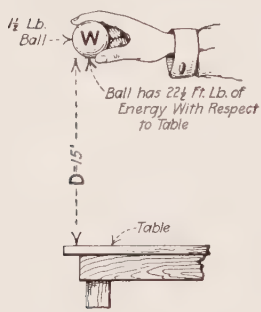


Fig. 29.—Ball possesses energy due to its position. (Drawing not to scale.)

25. There Are Two Fundamental Forms Of Energy, "Kinetic" And "Potential."—These forms are, sometimes called respectively *energy of motion* and *fixed energy*. Kinetic energy may be transformed into potential energy and vice versa. Bodies possess potential energy by virtue of their positions or conditions. Bodies possess kinetic energy by virtue of their motion.

Examples.—Since the now stationary ball, *W*, shown in Fig. 29 may do work, if permitted to descend, it possesses potential energy, due to its position. The main spring of a clock may possess potential energy, due to its condition of being wound. Water in a reservoir (Fig. 30) has energy, due to its position. Powder (Fig. 31) has potential energy, due to its explosive properties. A bullet projected from a gun has kinetic energy,

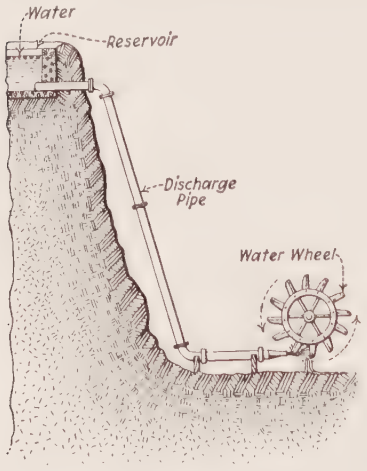


Fig. 30.—Energy of water from reservoir driving water wheel.

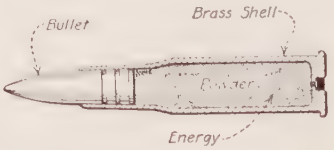


Fig. 31.—Powder in the rifle cartridge possesses potential chemical energy.

due to its motion, and is, thereby, able to pierce (Fig. 32) an iron plate. In so doing, part of its kinetic energy is converted into the work of piercing the plate. A falling hammer (Fig. 33) has kinetic energy.

Note.—Energy May Be Further Divided Into *mechanical, chemical, electric, radiant,* and *heat* energy. Each of these forms will be dis-

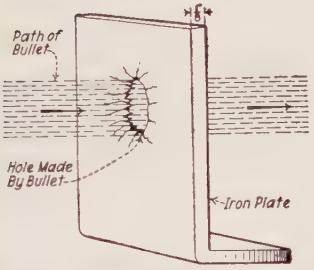


Fig. 32.—Energy of rapidly moving bullet enables it to pierce iron plate.

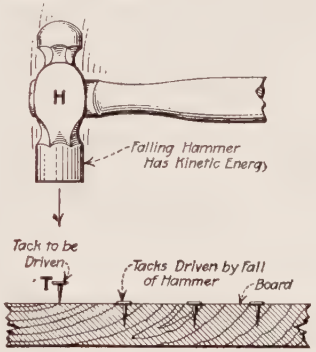


Fig. 33.—Kinetic energy of falling hammer drives tacks.

cussed in following sections. As explained in the following section, any one kind of energy may, by employing suitable machines or processes, be transformed into any other kind of energy.

26. Energy May Be Transformed From One Kind To Another.—Whenever there is motion there is energy transformation; all mechanical processes offer examples of it. Our everyday life is simply a succession of such energy transformations. Sometimes a process may be traced through an entire long series of energy transformations.

Examples.—A man eats a meal; a portion of the meal goes toward building up his muscular tissues thus storing chemical energy therein; he picks up a ball from the ground thus imparting potential energy to the ball; he throws the ball into the air thus imparting kinetic energy to the ball. The energy which was imparted to the ball was derived from his muscles. The kinetic energy of the ball, after he releases it, gradually becomes transformed into potential energy as the ball rises. Soon the ball ceases to rise. It begins to fall—it again acquires kinetic energy, this time at the expense of its potential energy. Having struck the ground, the ball has lost all of its potential energy (we may say, see also Sec. 85) but it now possesses much kinetic energy. It may deform the earth where it strikes and thus heat the ground and itself. Eventually, probably, all of the chemical energy which the man expended in lifting and throwing the ball will be transformed into heat energy. But this heat energy is

given to the earth or our atmosphere where it remains until it has a chance to do further work. It may stimulate plant life and thus help to produce more of that substance from which the man derived his chemical energy—that is, his food. Thus, the transformation of energy will, perhaps, go on forever. See also Table 33.

Note.—The State In Which Matter Exists May Change.—So also, the state in which energy exists may change. What is now liquid iron, of a pale orange color in the pouring-ladle, changes to plastic iron, of a cherry-red color in the mold, and again to hard grey iron in the finished casting. So, likewise, what is now chemical energy in a coal pile may be changed to mechanical energy by a steam engine, thence to electrical energy by a dynamo, and, perhaps, to active heat and radiant (light) energy in an electric lamp.

27. Mechanical Energy is that form of energy which may be realized directly as mechanical work. A watch spring, when wound, is capable of doing mechanical work in unwinding; it possesses potential mechanical energy. A rotating flywheel has energy of motion; it does the work of carrying the moving parts of an engine onward at the instants when the connecting rod is passing the dead centers. It has kinetic mechanical energy. See Table 33.

28. Chemical Energy (sometimes called "Internal" energy) is the energy which is normally "bound up" *within the molecules* of all substances. When a chemical process or reaction —a rearrangement and transfer of the constituent atoms of the molecules (Sec. 155)—occurs, some of the internal chemical energy may thereby be automatically released from the molecules of the substances which participated in the reaction. Then this chemical energy will be automatically transformed into heat energy, electrical energy, or mechanical energy—as determined by the reaction and the conditions under which the reaction occurred. Conversely, to effect certain other chemical processes it is necessary to add energy—heat energy, electrical energy or mechanical energy—to the substances involved to cause the transfer and rearrangement of the atoms of the molecules necessary to produce the new desired substances. When energy is thus added to substances to effect a chemical reaction, it then becomes "bound up" or latent as chemical energy within the molecules of the new resulting substances—and will remain so—unless part or all of it is later released, and transformed into some other kind of energy,

by some subsequent chemical process. These phenomena are further discussed in Sec. 157. See also Sec. 437 and Sec. 461.

Examples.—The burning of any fuel is a chemical process, combustion (see Div. 14). Combustion is a chemical union of oxygen with the fuel substance; the usual products are heat energy, a gas called carbon dioxide, other gases, and water. When combustion occurs part of the chemical energy which was stored in the fuel and in the oxygen is liberated as heat energy.

By the mechanical rubbing of silver chloride, a solid, it can be decomposed into silver, a metal, and chlorine, a gas. Heat energy from the friction of the rubbing, is absorbed, partly by the silver and partly by the chlorine, during this chemical process. The absorbed heat energy then resides latent in the chlorine and the silver. Mechanical energy has been transformed into chemical energy.

Powder (Fig. 31) possesses a large amount of chemical energy which may be liberated and utilized ultimately as mechanical energy to force a bullet out of a shell and through a rifle barrel; when the powder burns, it is converted into a gas at a very high temperature and pressure; the pressure imparts motion to the bullet. When an electric spark is formed in a suitable gas mixture in a gas engine (Fig. 34), an explosion results. This is a manifestation of chemical energy being transformed into mechanical energy. The high pressure, thus developed above the piston, results, finally, in the rotation of the crankshaft. When a zinc bar and copper bar (Fig. 35) are immersed in certain acid solutions, a chemical action results which forces an electric current to flow—an example of the transformation of chemical energy into electrical energy (see also Table 33).

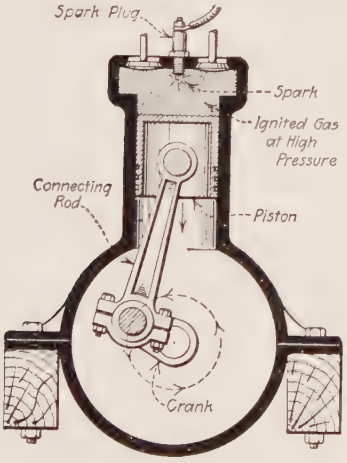


Fig. 34.—Energy developed by gas engine as a result of chemical reaction.

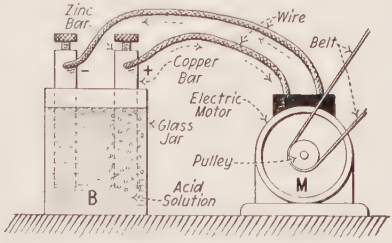


Fig. 35.—Electric current circulated due to chemical energy.

29. No Change In Chemical Composition—That Is, No Chemical Reaction—Can Occur Without The Liberation Or Absorption Of Energy.—The energy may be either heat, radiant, electrical, or mechanical energy, or some combination of them, depending on the reaction and the conditions under which it occurred. The preceding sums the results of many experiments. In this book it is, principally, the liberation and absorption of heat energy which are of interest, which is further treated in Sec. 156.

30. Electrical Energy is, in the kinetic form, the energy possessed by a current of electricity. Or, in the potential form, it is the energy possessed by a "charge" of electricity, stored in a condenser. Since an electric current is a flow of electricity—electricity in motion—such a current has kinetic energy. The energy of an electrical charge stored in a condenser is potential. This follows, since such a charge is, for the time being, fixed or stored.

Note.—An electric generator (Fig. 36) is a machine which transforms mechanical energy into electrical energy. Mechanical energy may be

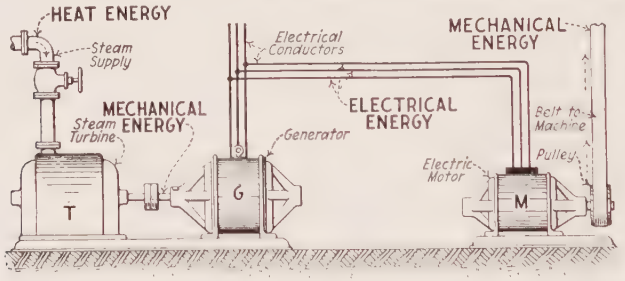


Fig. 36.—Illustrating conversion of energy—electrical energy transmitted from generator to motor.

imparted to the generator by an engine, turbine, or waterwheel. The generator, thus driven mechanically, forces an electric current (a stream of electrons, Sec. 42) to flow in the circuit. Thereby electrical energy is developed. Electrical energy may be reconverted into mechanical energy (Fig. 36) by electric motors. Electromagnets and electric heaters convert electrical energy into magnetic energy and heat energy, respectively.

31. Radiant Energy is the name which is given to that form of energy propagation from a hot body, by waves in the

æther, which produces the sensations of "light" and "heat" when the waves strike objects. Hence, radiant energy is classified as a form of kinetic energy. The action of light causes certain chemical changes. For example, light acting on a photographic plate (Fig. 37) induces chemical changes

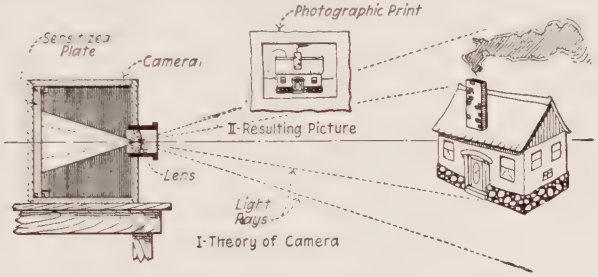


Fig. 37.—Light energy affects photographic plate.

which render photographs possible. Light acting upon plants causes them to grow and assume characteristic colors. See Div. 5 "Transfer Of Heat" for further discussion of radiant energy.

Note.—The Earth's Principal Source Of Radiant Energy Is The Sun (Sec. 65).

32. Heat Energy Or Heat (Fig. 38) is, as explained in Div. 2., believed to be a condition of motion. The molecules

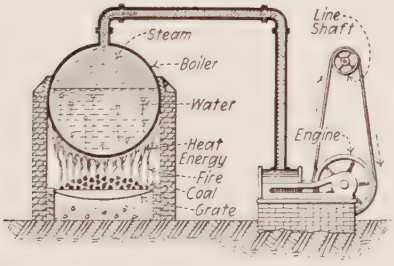


Fig 38.—Heat energy from fuel converted into mechanical energy by engine.

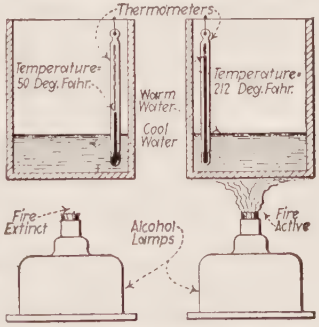


Fig. 39.—Heat energy raises the temperature of a body.

of all substances are (except theoretically at absolute zero. Sec. 61), vibrating constantly and separated from one another. This vibration and separation produce the phenomena of heat,

The speed of vibration of the molecules of a substance determines its temperature (Sec. 55). Hence, the vibration of the molecules is kinetic heat energy. The separation of the molecules is a state of potential heat energy. These ideas are explained at greater length in Div. 4. See examples of heat-energy transformations in Table 33.

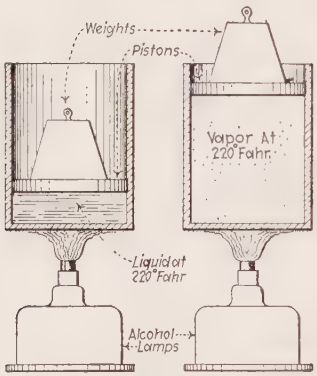


FIG. 40.—Heat energy changes a liquid to a vapor and thereby does mechanical work.

NOTE.—VARIOUS PHENOMENA RESULT FROM APPLICATIONS OF HEAT ENERGY.—The temperatures (Fig. 39) of substances are raised thereby. By the addition of heat, substances are changed from a solid to a liquid condition, or (Fig. 40) from a liquid to a gaseous or vaporous condition. When heated, bodies are caused (Sec. 159) to expand or increase in volume. These phenomena are discussed in detail hereinafter.

33. Table Of Examples Of Energy Transformations.—The examples here given are not to be understood as being the only instances of the transformations which they illustrate. (From THE THERMODYNAMICS OF HEAT-ENGINES by Reeve.)

Transformation		Example
From	To	
Mechanical.....	Heat	The heating of a body subjected to friction or impact.
	Electrical	The electric generator or the glass-plate electric machine.
	Chemical	The setting-off of a detonating compound, such as fulminate of mercury or nitroglycerine.
Electrical.....	Heat	The heating of any conductor by the passage of an electric current; the electric heater.
	Chemical	The electrolysis of a chemical compound by the passage of a current, as in electroplating or in the charging of a storage battery.

Transformation		Example
From	To	
Electrical	Mechanical	The electric motor; the solenoid.
Chemical	Heat	The combustion of fuels; animal heat.
	Electrical	The evolution of an electric current from a battery.
	Mechanical	Animal activity; the evolution of a gas from the combination of two solids or liquids as in the chemical fire engine.
Heat	Electrical	The thermopile or thermocouple (pyrometer).
	Chemical	The lime-kiln; the growth of vegetation.
	Mechanical	The expansion of a heated body; the steam engine.

NOTE.—THERMODYNAMICS is that branch of physical science which treats of the relation between heat and mechanical work. Hence, the portions of this book which consider the relation between these two forms of energy constitute, in reality, a treatment of elementary thermodynamics.

34. The Distinction Between Energy And Work dwells in the simple concept that work is a manifestation of energy. Work and energy—since they are both measured in the same unit, the foot-pound for example—are sometimes confused one with the other. Energy (Sec. 23) is a common property of all matter (note subjoined to Sec. 23). In fact, there is a recent theory, which is gaining recognition, that all matter is simply motion. If the theory is accepted, then all matter would be energy. Work (Sec. 20) is the medium through which the energy which resides in any portion of matter reveals its presence. When a quantity of energy is dormant, that is, when it is potential energy (Sec. 25), then work, so far as that particular quantity of energy is concerned, is in abeyance. The dormant energy may then be said (Sec. 23) to impart capacity for doing work to the body of matter within which it resides. When the same quantity of energy is active, that is, when it is permitted to overcome opposition through a distance, that energy is revealed as work. The active energy

may then be said to have developed or vitalized its dormant capacity for doing work.

35. "Power," in its technical sense, is the *rate of doing work*. In *work* and *energy* only two factors, i.e., *force* and *distance*, are the elements. In *power* there is a third factor, i.e., *time*. Observation proves that a machine which does a certain amount of work in 1 min. must be larger—more powerful—than another which does the same work in 2 min. A small machine may ultimately do the same amount of work as a larger one, but the small one requires more time to do it. The power of a machine is, then, determined by calculating the work which it does per unit of time. Hence the formula:

$$\mathbf{P} = \frac{W}{t} \qquad \text{(power)} \tag{14}$$

Wherein: **P** = the average power expenditure, during the time interval t, expressed as a number of work units of the given denomination, per the selected unit of time. W = the work done during the time interval t, expressed in any desired unit

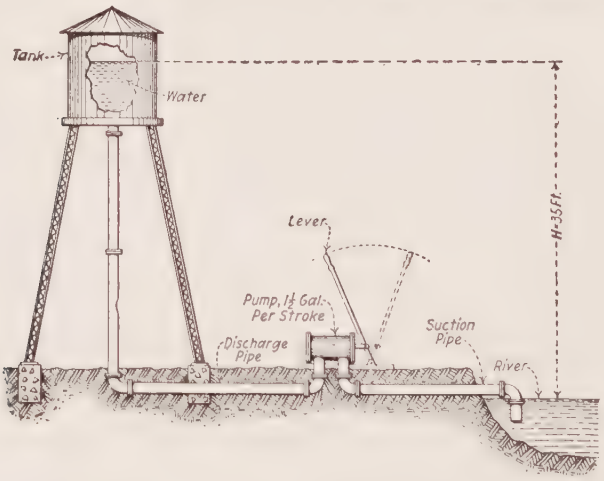


Fig. 41.—Example of power required to pump water.

of work. t = the time, expressed in any desired unit of time, in which the given quantity of work, W, is done.

Note.—If, in For. (14), W = foot-pounds and t = minutes, then **P** = foot-pounds per minute. If W = inch-pounds and t = seconds,

then **P** = inch-pounds per second. If W = mile-tons and t = days, then **P** = mile-tons per day. And so with other combinations of the units of work and time.

EXAMPLE.—To get water into a tank (Fig. 41) the water must be lifted 35 ft. The pump-lever makes 20 strokes per min. The quantity of water pumped at each stroke is 12 lb. What is the rate of doing work, that is, what power is being expended while the water is being pumped? SOLUTION.—By For. (13), the work done at each stroke = $W = FL = 12 \times 35 = 420$ *ft.-lb.* The time consumed in doing this quantity of work = $1 \div 20 = 0.05$ *min.* Hence, by For. (14), the *power developed* = **P** = $W/t = 420 \div 0.05 = 8{,}400$ *ft.-lb. per min.*

36. The "Horsepower" Is A Unit Of Power.—Any unit of power is an expression for a certain amount of work (Sec. 20) done in one unit of time. The unit of power which is commonly used in engineering is the horsepower. By definition, *the horsepower expresses the doing of work at the rate of* 33,000 *ft.-lb. per min.* That is, when work is done at the rate of 33,000 ft.-lb. per min., the power being expended is then 1 hp. Note that 1 hp. = 550 *ft.-lb. per second* = 33,000 *ft.-lb. per minute* = 1,980,000 *ft.-lb. per hour.*

NOTE.—THE HORSEPOWER UNIT WAS FORMULATED BY JAMES WATT as a basis from which to compute the capacities of engines for mine service. From empirical data which he had obtained, Watt calculated that a heavy draft horse, of the breed which had previously been generally used for hoisting coal out of mines, could do work regularly at the rate assumed, viz., at the rate of 33,000 ft.-lb. per min. It was later determined, however, that this assumed unit is much above the average daily working capacity of horses.

NOTE.—THE UNIT OF POWER WHICH IS GENERALLY USED IN THE METRIC SYSTEM is the kilogram-meter per second. One meter = 39.37 in.

37. The Average Power, In Horsepower Units, Which Is Developed By Any Apparatus Or Agency For Doing Work may be computed by the following formula:

$$\text{(15)} \qquad \mathbf{P} = \frac{FL}{33{,}000t} \qquad \text{(horsepower)}$$

Wherein: **P** = the average power, or rate of doing work, in horsepower, during the time interval, t, in which the work is done. F = the applied force, in pounds. L = the distance through which the force acts, in feet. t = the time, in minutes, during which the force is applied.

Note.—The nominal rate at which a steam engine or other apparatus does work is conventionally spoken of as *its horsepower rating.*

Example.—The number of pushes and pulls, per minute, of an engine piston (Fig. 42) is 60. The average total force on the piston is 6,000 lb. The length of the stroke is 10 in. What horsepower is being developed

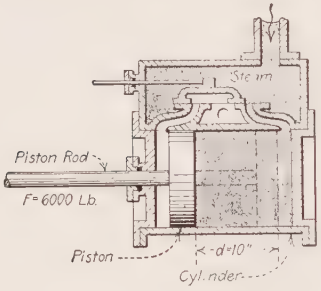


Fig. 42.—Example of power development by a steam engine cylinder.

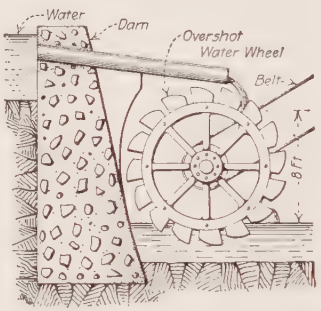


Fig. 43.—Power developed by an overshot water wheel.

while the engine is in operation? Solution.—The *distance traversed by the force, per minute* = $60 \times 10 \div 12 = 50$ *ft.* Hence, by For. (15), $P = FL/33{,}000t = (6{,}000 \times 50) \div (33{,}000 \times 1) = 9.09$ *hp.*

Example.—The effective weight of water flowing from the trough of an overshot wheel (Fig. 43) is 4,000 lb. per sec. The vertical distance, through which the water falls, is 8 ft. What horsepower is being developed? Solution.—The *given time* = 1 *sec.* = $\frac{1}{60}$ *min.* Hence, by For. (15), $P = FL/33{,}000t = (4{,}000 \times 8) \div (33{,}000 \times \frac{1}{60}) = 58.18$ *hp.*

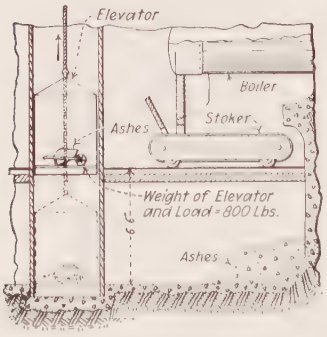


Fig. 44.—What power is required to raise the ash-lifting elevator?

Example.—A loaded elevator (Fig. 44) weighs 800 lb. A motor lifts it 6 ft.-6 in. in 30 sec. What horsepower is the motor developing? Solution.—The given *distance* = 6 *ft.* 6 *in.* = 6.5 *ft.* The given *time* = 30 *sec.* = $\frac{30}{60}$ = 0.5 *min.* Hence, by For. (15), $P = FL/33{,}000 = (800 \times 6.5) \div (33{,}000 \times 0.5) = 0.315$ *hp.*

Example.—A motor is belted to a machine. The belt travels 450 ft. per min. The difference, in tension, between the two sides of the belt is 50 lb. What horsepower is being transmitted? Solution.—By For. (15) = $FL/33{,}000t = (50 \times 450) \div (33{,}000 \times 1) = 0.68$ *hp.*

QUESTIONS ON DIVISION 1

1. What is *force*? What effect does it have upon a moving body? Give examples.

2. What are the common units of force? Give examples.

3. What is *pressure*? What kind of substances are generally spoken of as exerting pressure?

4. How does the fluid pressure at a point vary with the direction in which it is measured?

5. State two general classes of pressure units and give examples of each.

6. What is *atmospheric pressure*? How is it measured? Give a general description of the mercurial barometer.

7. Why is a man standing on the ground under a heavier atmospheric pressure than a man flying in an airplane?

8. What are pressure gages? Explain two ways in which pressures may be measured.

9. What is *gage pressure*? *Absolute pressure*? State how each is measured.

10. Define *work*. What factors are needed in calculating the amount of work done? Explain with an example.

11. What is the unit of work? State examples of its application.

12. Give and explain the formula for computing work.

13. What is energy? Can it be destroyed?

14. What is the unit of energy? Give an example of its application.

15. What is meant by *kinetic energy*? Give example. *Potential energy*? Give example.

16. Give practical examples of *mechanical energy* and tell whether they are kinetic or potential.

17. What is meant by *chemical energy*? Give example.

18. Give an example of kinetic energy in electrical form. Likewise potential energy.

19. Why is light classified as a form of energy?

20. Discuss heat with reference to energy. Is heat energy?

21. What is *power*? How is the power of a machine determined? Give an example.

22. What is the principal unit of power? Give an example of its application

23. Give and explain the formula used in power calculations.

PROBLEMS ON DIVISION 1

1. What force, in pounds, is required to lift, vertically, a cart of coal which has a total weight of 1 (short) ton?

2. Is a wrench, which is lying on the floor and which weighs 5 lb , subjected to any force? What effect is due to the weight of the wrench?

3. An engine with its concrete foundation weighs 20,000 lb. Its base area is 50 sq. ft. What pressure, in terms of the weight and area as here given, does the foundation impose on the supporting soil?

4. A steam gage registers 128 lb. per sq. in. What is the absolute pressure? (Assume standard atmospheric pressure.)

5. What pressure, in pounds per square inch, is indicated by a barometer reading of 28.5 in. of mercury column?

6. What height of mercury column will balance a 30-ft. water column?

7. If the man in Fig. 2 pulls 12 lb. with his left hand, what will he be pulling with his right? Why?

8. If a car loaded with coal, weighs 100,000 lb. and the resistance to rolling totals 5 per cent. of its weight, how much draw-bar pull will be required to keep the car moving slowly?

9. If a bucket of coal weighs 50 lb., how much work will be required to carry it up a set of steps to a point which is 15 ft. higher?

10. A punch exerts an average push of 35,000 lb. in punching a hole in a piece of armor plate ½ in. thick. How much energy is required to punch the plate? (Assume that the 35,000 lb. is exerted through the ½-in. distance.)

11. The tension of one side of a belt is 65 lb., and on the other 140 lb. The belt is traveling 300 ft. per min. What is the horsepower transmitted?

12. What is the horsepower of the head end of a steam cylinder, when the average pressure on the piston rod is 3,500 lb., the stroke 15 in., and the revolutions per minute of the flywheel, 90?

13. A pump will deliver 1,500 gal. of water per minute to a water level, 350 ft. above the pump. If water weighs 8.3 lb. per gal., at what rate is the pump doing work, in foot-pounds per minute and in horsepower?

14. A 6-hp. motor is used to pump water from a well 75 ft. deep. If the motor is running at full capacity, and all losses neglected, compute the number of gallons of water raised in three hours. (Water weighs 8.3 lb. per gal.)

DIVISION 2

MATTER, HEAT, TEMPERATURE

38. A Knowledge Of Certain Fundamental Concepts Regarding The Material World Is Necessary To An Understanding Of The Phenomena Of Heat.—If the various substances or materials which we recognize about us, such as *air, iron, wood, water* did not exist, there could be no heat, for heat is a condition of materials. The heat sensations which we experience, as emanating from substances, are manifestations of this condition.

39. "Matter" Is That Of Which Every Substance In The Material World Is Formed; this is the technical definition of matter. But all matter is not of one kind. Different kinds

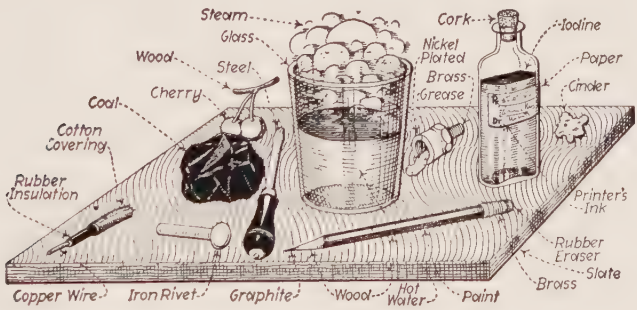


FIG. 45.—Different substances all made up of matter.

of matter (Fig. 45) form different substances. Thus there are thousands of different kinds of matter.

NOTE.—A SUBSTANCE IS ANYTHING WHICH HAS WEIGHT AND VOLUME.—Therefore, anything that has weight, and which occupies space, is *matter*. Consequently, anything that can be recognized by sight, touch, taste or smell is *matter*. But not all substances are evident to the four senses here enumerated. Many substances, as *air* and *oxygen*, are quite unapparent to these senses. Yet such substances have weight and occupy space, and hence are *matter*.

Note.—Universal Space Which Is Not Occupied By Matter Is Occupied By Æther (Sec. 46). Hence, the universe comprises only two fundamental components: (1) *Matter.* (2) *Æther.*

40. Matter Is Composed Of Minute Particles Called Molecules.—These particles are so small that one of them, if it were possible to separate it from all others, would be invisible even under the most powerful microscope. It is not anticipated that magnifying instruments strong enough to render molecules observable to the human eye will ever be perfected.

Note.—The Molecules Of Different Substances, as *wood, glass, steel, rubber, air, oil,* are differently constituted. There are as many kinds of molecules as there are substances or kinds of matter.

41. Molecules Are Composed Of Smaller Particles Called Atoms (Fig. 46). Atoms are, probably, as much smaller than some molecules as molecules are smaller than the smallest particle of matter which may be discerned through the strongest microscope yet produced. Only a few more than about 80 different kinds of atoms have thus far been isolated (from atoms of different kinds—a single atom has not been isolated) and identified. It is said that no more than 92 different kinds are possible. All matter is, therefore, built up of molecules in which one or more of these 92 different kinds of atoms subsist in various combinations and arrangements.

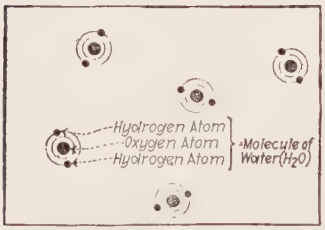


Fig. 46.—An imaginary picture of the molecules of water each of which is composed of three atoms—one of oxygen and two of hydrogen. The 3 atoms remain in a group. The molecules move about—often colliding.

Note.—A Substance The Molecules Of Which Are Composed Of But One Kind Of Atom Is Called An Element (Table 42). The molecules of most substances, as *soap, rubber, steel, brick, flesh, albumen,* are composed of more than one kind of atom. The molecules of a substance may contain hundreds of atoms, even though many be of one kind. The molecular composition of every substance, as regards the kinds of atoms and the numerical combinations thereof, is invariable for that substance. Generally, when the molecular composition of a substance is changed the nature of the substance likewise is changed.

42. Table Giving The Most Common Chemical Elements, With Symbols.

Element	Symbol	Element	Symbol	Element	Symbol
Aluminum	Al	Fluorine	F	Nitrogen	N
Antimony	Sb	Glucinum	Gl	Oxygen	O
Argon	A	Gold	Au	Phosphorus	P
Arsenic	As	Helium	He	Platinum	Pt
Barium	Ba	Hydrogen	H	Potassium	K
Bismuth	Bi	Iodine	I	Silicon	Si
Bromine	Br	Iron	Fe	Silver	Ag
Calcium	Ca	Lead	Pb	Sodium	Na
Carbon	C	Lithium	Li	Sulphur	S
Chlorine	Cl	Magnesium	Mg	Tin	Sn
Chromium	Cr	Manganese	Mn	Tungsten	W
Cobalt	Co	Mercury	Hg	Zinc	Zn
Copper	Cu	Nickel	Ni		

Note.—Every Atom Is Believed To Be Composed of Smaller Particles Called Electrons Together With A Positive Nucleus.—

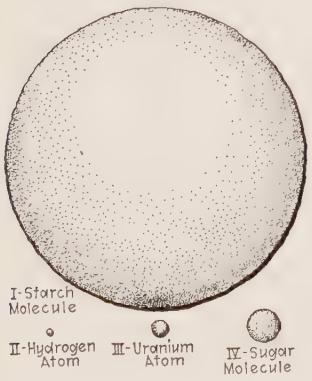


Fig. 47.—Comparison of sizes of smallest and largest atoms and molecules (Comstock & Trowland).

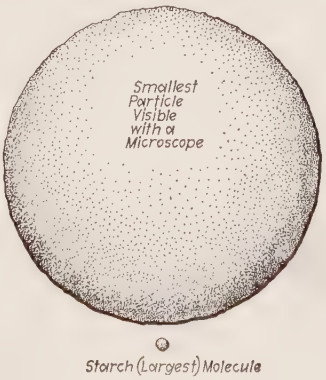


Fig. 48.—Comparative sizes of largest molecule and smallest microscopically visible particle (Comstock & Trowland).

An electron is a natural particle of negative electricity. The electrons which compose an atom are presumed to rotate in regular orbits about a center or *nucleus* of positive electricity of the atom, in much the same way as the four moons rotate around the planet Saturn. Hence it appears that, in its ultimate composition, all matter is, probably, composed of electricity. In the discussion which follows, the atom will be regarded as the ultimate division of matter. The electron theory is explained in the author's PRACTICAL ELECTRICITY.

NOTE.—ATOMS (Fig. 47) have an average diameter of about one *one-thousand-millionth* ($\frac{1}{1,000,000,000}$) of an inch. A molecule of salt has a diameter of about one *ten-millionth* ($\frac{1}{10,000,000}$) of an inch. The smallest particle of matter (Fig. 48) that can be viewed through a microscope has a diameter of about one *hundred-thousandth* ($\frac{1}{100,000}$) of an inch. It is estimated that a cubic inch of air contains between 16 billion billion (16,000,000,000,000,000,000) and 16 thousand billion billion (16,000,000,000,000,000,000,000) molecules.

43. Neither The Molecules Which Form A Substance Nor The Atoms Which Form The Molecules Are In Contact With One Another.—Relatively large spaces intervene between neighboring atoms, and between neighboring molecules, even in the most compact of solid substances.

NOTE.—NOTWITHSTANDING THAT IMMENSE DISTANCES, CONSIDERED IN A RELATIVE SENSE, SEPARATE THE ATOMS WHICH FORM A MOLECULE, a mutual attraction, probably of an electric nature, still prevails among them. This mutual attraction will continue in force as long as the requisite number of atoms, to form the particular kind of molecule, are present, and no abnormal condition develops. The attraction may be strong or weak. If the latter, the molecules of a substance, if composed of different kinds of atoms, may be broken up by heat or by chemical or electrical means and then the different kinds of atoms may group by themselves to form molecules of the elemental substances (Table 42). Or, by similar methods, atoms may be added to the molecules of a substance, and another kind of substance be thereby produced.

44. The Molecule Is The Structural Unit By Which Substances Are Differentiated From One Another.—A molecule of water is composed (Fig. 46) of *two atoms of hydrogen and one atom of oxygen.* The composition of water molecules, from these elements alone and in these proportions, is absolute and invariable. Hence, molecules so constituted differentiate water from all other substances. Similarly, a molecule of common salt is composed of *one atom of sodium and one atom of chlorine.* This, likewise, is an atomical arrangement, in

the composition of salt-molecules, which is precise and unalterable. Therefore, in this particular composition and arrangement lies the inherent difference between common salt and all other substances.

Note.—The Number Of Atoms In A Molecule may be few or many. Thus, each common-salt molecule is composed of but 2 atoms, while each white-of-an-egg molecule is composed of about 1,000 atoms.

45. Motion Is An Attribute Of Molecules And, Probably, Also Of Their Component Atoms.—Upon this important concept is predicated much of our knowledge regarding heat phenomena. Whether or not the atoms within a molecule are in motion with respect to one another is not definitely known. The molecules are supposed to be in motion except at the theoretical absolute-zero temperature (Sec. 61), at which temperature they are supposed to become motionless.

Note.—Molecules May Follow Regular Paths Along Straight Or Curved Lines, or their movements may be very erratic and irregular. In the latter alternative, the movements of molecules may be compared to those of individuals rushing hither and thither in a panic-stricken throng, now colliding with one another and now recoiling from the impact.

Note.—The Speed Of A Hydrogen Molecule at 32° F. is about 1⅛ mi. per sec. or nearly 6,000 ft. per sec. Mercury molecules move at about $\frac{1}{10}$ the speed of hydrogen molecules, or about 400 mi. per hr.

46. Æther Is The Name Given To That Which Fills All Universal Space Unoccupied By Matter.—It occupies the infinitesimal—though large as compared with the size of the molecules—spaces which intervene between the atoms and molecules of substances, as well as the inconceivably vast reaches of interstellar space. Nothing is definitely known regarding the precise nature of æther. It is believed to be devoid of weight. Being thus imponderable, —without sensible or appreciable weight—it cannot (Sec. 23) be regarded as matter.

Note.—The Spaces Between The Atoms And Molecules of compact substances, as *glass* and *steel*, are not large enough to permit ingress of air molecules. But, on the basis of the common-sense assumption that an absolute void can nowhere exist, there must be something within these spaces. This something is what is called *æther*.

Note.—According To Certain Later Theories It Is Claimed That There Is No Æther.—It is said to have been proved by Einstein's theory

of relativity that there is no æther. But whether or not there is an æther depends upon the definition which is accepted for "æther"— upon the properties which this hypothetical æther is assumed to possess. Various definitions and properties have been proposed for the æther. As a matter of common sense there must be something, in the space of the universe which is not occupied by atoms, whereby light waves, heat waves, electric waves, and magnetic waves are transmitted. (The scientists are reasonably certain that these waves can be readily transmitted through a perfect vacuum.) It is inconceivable that these waves —or any wave motion—can be propagated through "nothing at all." Hence, in this book the æther will be considered as that medium or something which fills what would otherwise be voids in space and whereby light, heat, electric, and magnetic waves are transmitted. Furthermore, since Einstein's theory of relativity does not affect the study of heat phenomena, it may for the present purposes be assumed that the statements herein given concerning æther are true.

47. Matter Is Indestructible.—The molecular composition of a portion of matter may be changed. Through new combinations of its elemental atoms the substance of which any portion of matter is formed may be changed into some other kind of substance. Or it may be changed into several other kinds of substances. But the precise quantity (and mass—see note below) of that particular portion of matter will continue undiminished.

Note.—If Several Substances Be Combined Chemically, the weight of the resultant substance will be the sum of the weights of the individual substances. A quantity of oxygen may unite with the combustibles in a lump of coal to produce combustion thereof. The combustibles will volatilize and disperse in gaseous form, leaving a residue of ash and clinker. But if these constituents—the gases and residual substances—could be reassembled, their combined weight would equal precisely the weight of the original lump of coal plus the weight of the oxygen which was supplied for its combustion.

48. Matter Cannot Be Created.—Hence the quantity of matter in the universe must be constant. It cannot be increased, neither can it be diminished. It may, however, undergo many changes of form.

Example.—*Rags, wood, and certain other substances,* will, after undergoing certain mechanical and chemical processes, reappear as *paper. Hydrogen* and *oxygen* will, under certain conditions, combine and form *water.* Note that in both examples no *new matter* has been created. All that has occurred is that the form of existing matter has been changed.

49. There Are Three States Of Matter: (1) *Solid.* (2) *Liquid.* (3) *Gaseous.*—Theoretically, any substance, as *water* (Fig. 49), may, under different conditions, exist in each of these three states. As will be explained in following Secs. 225 and

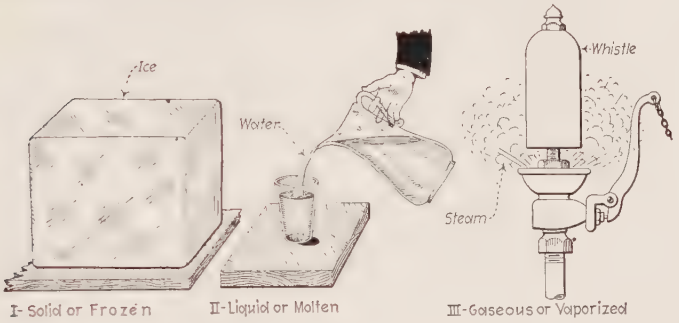


FIG. 49.—Illustrating the three states of matter—water in this case.

351, *a substance in the gaseous state may be either a vapor or a gas.* In general, if the certain temperature and pressure conditions to which a given gaseous substance is subjected are such that the substance is then "near" the liquid state, it is then, under

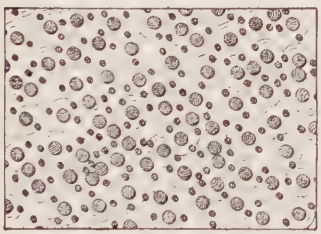


FIG. 50.—Imaginary condition of molecules in a solid (ice) magnified many millions of times.

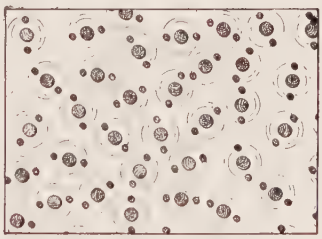


FIG. 51.—Imaginary condition of molecules in liquid (water) magnified many millions of times.

those conditions, called a vapor. If the certain conditions are such that the gaseous substance is "far away" from the liquid state then, under these conditions, it is called a gas.

NOTE.—FIGS. 50, 51, AND 52 ILLUSTRATE IMAGINARY ARRANGEMENTS suggested by the apparent action of atoms and molecules. The intervening distances are not proportional to the sizes of the atoms and molecules as illustrated. The actual proportional distances are, in a practical sense, immeasurably greater than appears in the illustratoins.

Note.—Resistance To Changes Of Shape Is A Common Characteristic Of Substances In The Solid State.—The shape of a *piece of steel* (Fig. 53) is difficult to change. The shape of a *sheet of thin paper* is changed with relatively little difficulty. The paper may be folded with

Fig. 52.—Imaginary conditions of molecules in gas (steam or water vapor) magnified many millions of times.

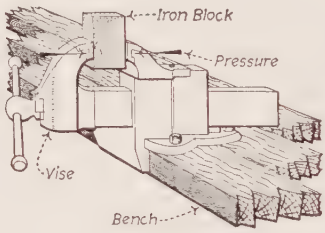


Fig. 53.—Solids resist compression.

apparent ease. But its resistance to folding will, nevertheless, be definite and distinct.

Resistance To Compression And Susceptibility To Changes Of Shape Are Common Characteristics Of Substances In The Liquid State.—Water is practically incompressible. It will, however, instantly take the form of (Fig. 54) of any container in which it is placed.

Susceptibility Both To Compression And Changes Of Shape Are Common Characteristics Of Substances In The Gaseous State.—Gaseous substances,

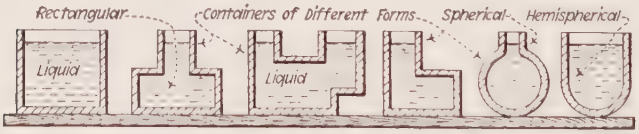


Fig. 54.—A liquid assumes the form of any container in which it is placed.

as *air*, *saturated steam*, which is a vapor, and *highly-superheated steam*, which approximates a perfect gas, tend to expand indefinitely when released from a container.

50. The Existence Of A Portion Of Matter In The Solid, Liquid, Or Gaseous State Depends On The Motion Of Its Molecules (Figs. 50, 51 and 52). As stated in Sec. 45, molecules move or vibrate. The state of the matter—solid, liquid,

or gaseous—is determined by the rapidity and extent of motion of its molecules. In other words, as will be shown, the state of a given portion of matter is determined by the amount of heat—heat energy—which it contains.

Explanation.—"*In solids* the component molecules are in some way so closely bound together, and their vibrations, though still taking place, are so narrowly and rigidly limited in relation to one another, that the external form of the aggregation—the body taken as a whole—is capable of resisting the action of forces of considerable magnitude which may tend to deform it.

In liquids the molecules, though still held together by a mutual attraction which limits their distance of separation (in so far as internal molecular forces are concerned), they are now quite free to assume any position relatively to one another which they choose, or to *roll* about one another. This rolling is what we call *flow*.

In the gaseous form the molecules are very much more widely separated than in liquids or solids; they are more actively in vibration, and they tend to separate to the widest possible degree permitted by external resistances, such as the walls of a containing vessel." (From Reeve's Thermodynamics of Heat-engines.)

Note.—In Solids The Molecules Are Thought To Vibrate At A Comparatively Slow Rate and through a small range. Each molecule

Fig. 55.—Molecules of substances in the three states act like men in a crowd, pedestrians in a street, and thieves fleeing from an officer of the law. (This is a view from above.)

is analogous to a man (Fig. 55-*I*) in a densely-packed crowd. He may turn around and move slightly from side to side and backward and forward. But he cannot move far from one position, because he is resisted on all sides by other people.

In liquids, the molecules vibrate more rapidly and through much wider ranges. Each molecule moves to and fro encountering little resistance. Molecules of liquids are analogous to individuals (Fig. 55-*II*) passing one another on a busy city square. They collide only occasionally.

In gases, the molecules are so far apart that they have little cohesive attraction for one another. They fly about very rapidly and freely.

They may be thought of as acting like thieves (Fig. 55-*III*) scattering through a field to escape pursuers. Because of their great freedom of movement and high velocities they bombard the sides of the containing vessel. This creates therein what is called a "pressure," (see Sec. 227).

Note.—The Molecules Of Different Portions Of Solid Matter Are Incapable Of Intermingling.—This is due to their restricted vibratory motion. Blocks of metal (Fig. 56) may be forced in contact with each other under enormous pressure, but no intermingling of the molecules of the two blocks will generally occur.

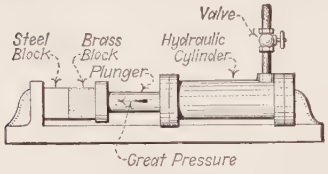


Fig. 56.—Solids remain to themselves, *i.e.*, do not mix, even when subjected to great pressure.

The Molecules Of Different Portions Of Liquid Matter May, Usually, Mingle Freely. This is due to their fluid motion. Fluidity is apparent in the facility with which a quantity of milk, when poured into a cup of coffee, permeates the entire mass. Similarly a drop of red ink in a glass of water will tint uniformly all of the water.

The Molecules Of Different Portions Of Gaseous Matter Will Mix Unrestrainedly. This may be observed in the blending of colors which attends the forcing of differently colored gases into a common vessel.

51. Molecules Behave Differently In The Three Different States In Which Matter Occurs.—That is, their behavior (as is explained later, Sec. 52) is determined by the amount of heat—heat energy—which is contained in the substance which they compose. The rigidity of a solid substance is due to the relatively strong mutual attraction which prevails among its molecules. The fluidity of a liquid substance is due to the relatively weak mutual attraction which prevails among its molecules. The volatility of a gaseous substance is due to the lack of cohesive force between its molecules. The molecules of an unconfined gas tend to disperse through all surrounding space. All trace of an unconfined gas may thus be lost.

Note.—The Attraction Among The Molecules Of A Solid is analogous to that which exists between two magnets (Fig. 57) in close proximity. The magnets will offer quite appreciable resistance to further separation. They will likewise resist a force tending to produce a sidewise movement of one relative to the other.

The Attraction Among The Molecules Of A Liquid may be compared to the weakened mutual attraction which the magnets in Fig. 57 would exhibit if a space equal, say, to their own length intervened between them.

The Freedom Of The Molecules Of A Gas is analogous to that which exists (Fig. 58) between the lead balls of an exploding shrapnel shell. The balls scatter unrestrainedly in all directions at first. Later, of course, they all fall to the earth.

52. The State Or Condition Of Molecular Vibration And Separation Is Called Heat.—Heat is thus conceived to be an

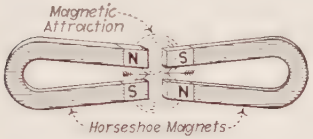


FIG. 57.—Molecules have attraction similar to that of magnets.

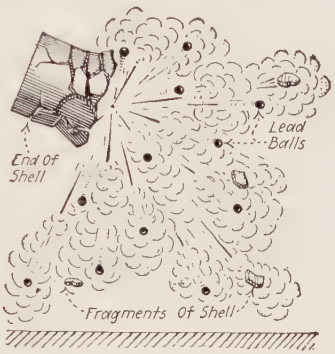


FIG. 58.—The freedom of movements of the lead balls from an exploding shrapnel shell illustrates the freedom of motion of gaseous molecules.

inherent attribute of matter so long as molecular vibration continues (Sec. 50). An *addition of heat*—heat energy—means either an *increase in molecular-vibration velocity* (kinetic heat energy) or an *increase in molecular separation* (potential heat energy) or both. When we say that heat has been added to a portion of matter, we actually mean that the vibration velocity of the molecules of the matter or the distance between the molecules has been increased through some external agency. Kinetic or potential energy has been added to the portion of matter. Conversely, when we say that heat has been abstracted from a portion of matter, we actually mean that the rate of vibration of the molecules of the matter or the distance between the molecules has been decreased (that heat energy has been abstracted) through some external agency.

53. The External Evidences Of Heat Transfer are, when heat is added, an enlargement or expansion (Sec. 185) and, when heat is abstracted a diminishment or contraction of the apparent bulk or body of the portion of matter. These indicate that, when an object is heated, the molecules spread farther apart on the average, due to their more rapid vibration. When the body is cooled their less rapid vibration permits their

mutual attraction to pull them closer together. (See Sec. 54, for the principal effects of heat transfer.)

Note.—Agitation Of A Substance Speeds Up The Motion Of Its Molecules.—If a soft wire (Fig. 59) be bent rapidly back and forth, the bent portion of its bulk will become heated. This will be due to the agitation of the molecules in the bent portion. If a piece of lead (Fig. 60)

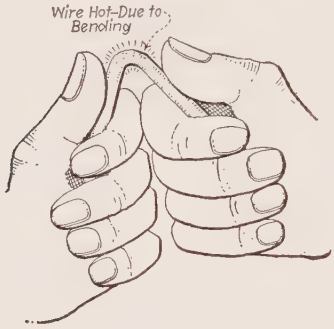


Fig. 59.—Bending wire agitates the molecules, hence makes it hot.

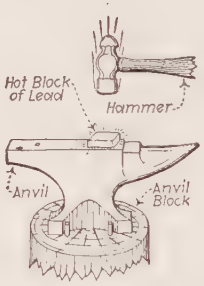


Fig. 60.—Lead becomes hot when hammered.

be hammered, its temperature will rise. This will be due to the molecules having been jarred, slipped and agitated. The rubbing together (Fig.

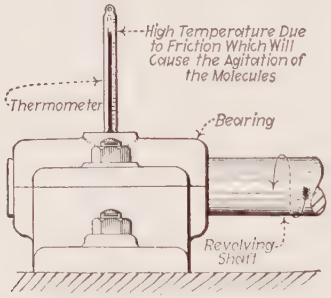

High Temperature Due to Friction Which Will Cause the Agitation of the Molecules
Thermometer
Bearing
Revolving Shaft

Fig. 61.—A bearing heats because the molecules are made to vibrate more rapidly by the rubbing of the metal surfaces.

61) of substances agitates the molecules and causes increase of heat. Agitation of liquids and gases causes heat to develop therein.

54. Broadly, There Are Only Three Possible Effects Of Heat Transfer To Or From Any Substance—any one, two, or all three of which may be produced, depending on the conditions under which the heat transfer takes place, as is explained in Sec. 96: (1) *Change in temperature of the substance* (Sec. 55)

or in molecular vibrational velocity; the part of the total heat which produces this change is called "*vibration heat.*" (2) *Change in state* (Sec. 49) or in the molecular-attraction forces; the part of the heat which produces this change is called "*disgregation heat.*" (3) *External work* or change in molecular position against external forces; the part of the total heat which produces this change is called "*external-work heat,*" or "external heat." Of course there is really only one kind of heat; the terms "vibration heat," "disgregation heat," and "external-work heat" are employed merely to designate how portions of the total heat which is transferred to a substance are expended in different ways.

Example.—Consider the effects of adding heat to a quantity of water confined in a metal cylinder (as in Fig. 62) under a piston, *P*, and a weight, *W*. The heat which is first added goes almost entirely, as would be

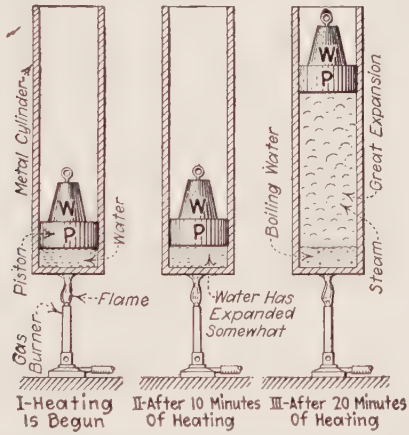


Fig. 62.—Illustrating effects of heating water.

indicated by a thermometer, toward *raising the temperature* of the water; this would then be *vibration heat.* The water would also expand, as indicated at *II* (Fig. 62) but the expansion would be very small. Hence very little of the added heat is *external-work heat,* useful in lifting the weight, *W*. But, after continued heating, the water would reach a point (temperature) where it would become no "hotter;" that is, its temperature would cease to rise. The heat which is then added (*III*, Fig. 62) separates the molecules of the water against their mutual attractive forces and against the weight, *W*, which tends to hold them together. Hence, the heat which is now added is partly *disgregation heat,* which is

useful in changing *the state* of the substance (from water to steam), and is partly external-work heat which is useful in *doing external work* (by lifting the weight, W, against the force of gravity).

55. The Temperature Of A Body (Figs. 63 and 64) is a measure of the tendency of that body to transmit heat to (Fig. 63) or to withdraw heat from another body. The *temperature* of any substance *is a measure of the kinetic or vibrational*

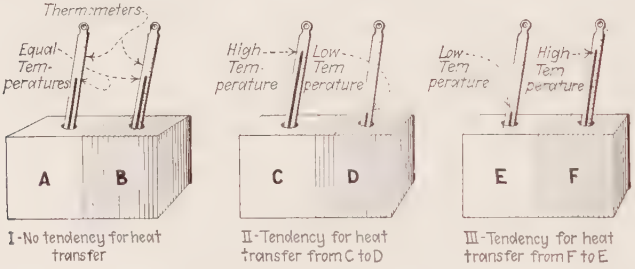


Fig. 63.—The temperature indicates the tendency of a body to transfer heat.

energy of its *individual* molecules—not the total kinetic energy of all of its molecules taken together, for this a measure of its heat energy or heat content. Hence, do not confuse *temperature* with *heat*. *Temperature* is *intensity* of heat. Temperature describes the degree of hotness or coldness of a body. Temperature may be thought of as the pressure of the heat in a body. Just as the pressure indicated by a steam gage is no indicator of the total quantity of steam which the boiler or boilers contain, so the temperature of a body (indicated by a thermometer) is no measure of the total amount of heat contained in the body.

Note.—In General, It May Be Stated That Temperature Is An Approximate Measure Of The Amount Of Heat Per Unit Weight which a given material contains. In general, the more heat—heat energy a given body contains the higher will be its temperature. But, this principle does not hold at or near temperatures where changes of state (Sec. 49) occur. Hence, the temperature of a substance is not, necessarily, any indication whatsoever of the amount of heat which the substance contains. The heat content may, when a change of state is occurring, be increased or decreased and yet the temperature remain constant (Sec. 103). For example, water at its boiling temperature—during a change from the liquid to the vaporous state—may have (Sec. 52) much heat added to it and the water be thereby converted into steam;

without change in the temperature. The steam has the same temperature (Sec. 104) as the boiling water.

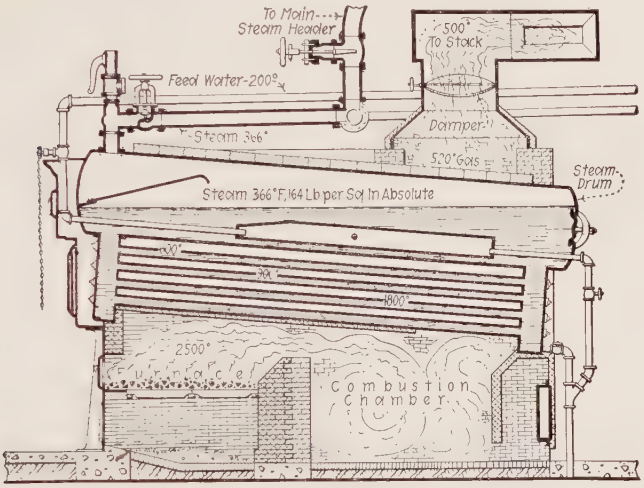


Fig. 64.—Showing how the temperature—the ability to transfer heat—of boiler gases decreases along the flue-gas path. (The temperatures indicated above are approximately those which should be maintained in a horizontally-baffled water tube boiler. *Brown Instrument Co.*)

Note.—Temperature Is Really Thermal Head Or Pressure.—Temperature is to heat what voltage is to electricity. Where there is no difference in temperature, there can be no flow of heat (O. B. Goldman).

Example.—Fig. 64 shows the temperatures which should be maintained for the efficient operation of a modern horizontally baffled water-tube boiler.

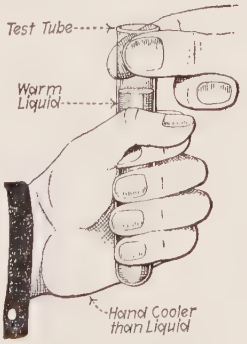


Fig. 65.—To cool (slightly) a hot test tube and contents, hold in relatively cool hand.

56. "Cold" Is A Term Used To Express A Condition Of Temperature. It is often thought of as the opposite of heat. But it is not. In fact, *cold* is merely a word used to designate the relative condition of a substance when it has less than the normal *intensity* of heat. Therefore, to render a body cold, (Fig. 65) it is merely necessary to take some heat away from it—not to add *cold* to it. In general, a "cold" body is merely one which has a temperature

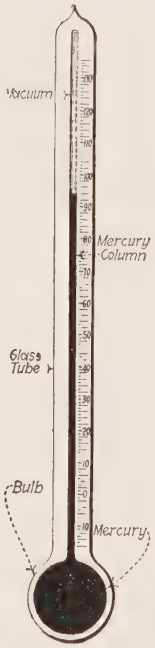


Fig. 66.—Mercury thermometer.

lower than that which is considered as the usual, normal, or ordinary temperature.

57. The Instruments Ordinarily Used For Measuring Temperature Are Called Thermometers (see also Sec. 652 Div. 19).—In its simplest form (Fig. 66) a thermometer is a hollow glass tube, hermetically sealed at both ends, and expanded into a bulb at its lower end. The bulb is filled with a suitable liquid, as mercury, and all air is exhausted from the tube before it is sealed. This is to permit free expansion of the liquid to the top of the tube. When the bulb is heated the liquid expands (Sec. 185) and rises in the tube. When the bulb is cooled the liquid contracts and lowers in the tube. When a proper scale is used in connection with this arrangement, the temperature of surrounding materials may be accurately determined. Other instruments for measuring temperature are further discussed in Div. 19.

Note.—An Early Type Of Thermometer is illustrated in Fig. 67. A glass tube, with a large bulb on one end, was

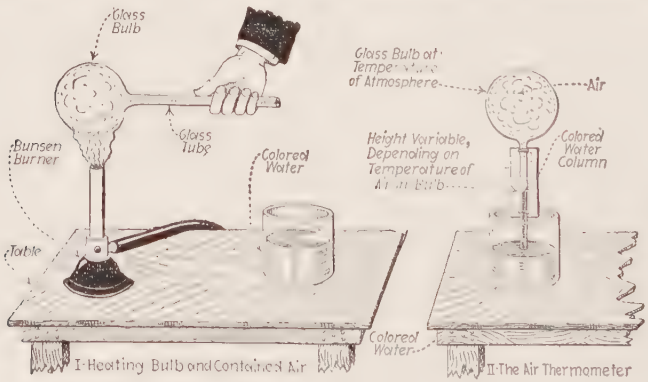


Fig. 67.—Making an air thermometer.

heated. The tube was then inverted and the open end inserted in a vessel of colored water. In cold weather, the air in the bulb con-

tracted. The colored water was thus forced up in the stem by the external air pressure. In warm weather the water-column was correspondingly low. By placing a scale beside the tube, it could thereby be known when the temperature was high or low. Obviously, this thermometer was not suitable for showing temperatures below the freezing point of water.

58. Thermometric Scales Are Series Of Graduated Divisions (Fig. 68) which are marked on the tubes or stems of thermometers, or upon separate flat surfaces set adjacent to the stems. By means of such scales, the temperatures are read directly from the instruments in "degrees" (Sec. 59).

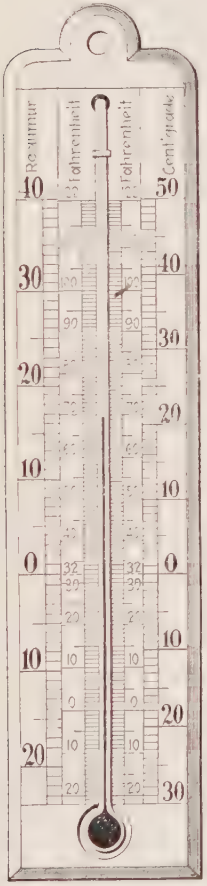


FIG. 68.—Thermometer with 3 scales.

59. There Are Three Thermometric Scales In General Use (Fig. 68).—(1) *The Fahrenheit scale.* (2) *The Centigrade scale.* (3) *The Reaumur scale.*

FIG. 69.—Fahrenheit and Centigrade scales compared.

The Fahrenheit scale is in popular and engineering use in English-speaking countries. The Centigrade scale is in popular use in most European countries. It is the world-wide standard in all scientific usage. The Reaumur scale is used principally in Russia.

Note.—The Fahrenheit Thermometric Scale (Fig. 69) was invented by Gabriel Daniel Fahrenheit, of Danzig, Germany, in 1714. Fahrenheit assumed that the temperature of a mixture of equal weights of snow and sal-ammoniac (ammonium chloride) was the lowest obtainable. Therefore, he accepted this as the zero (0) of temperature. The blood-temperature of the human body, as shown by the rise of the mercury in the column, was then selected as marking another definite point in the scale and called—incorrectly, see below—100. The distance between these points was divided into 100 equal spaces. Each space was called a degree (°) of temperature. According to this scale, water boils (under atmospheric pressure) at 212° and freezes at 32°. The scale between these temperatures is, therefore, divided into $212 - 32 = 180$ equal spaces or degrees. One degree of temperature, Fahrenheit (1° F.), is indicated by $\frac{1}{180}$ of the expansion of the mercury column of a thermometer which occurs when the temperature is raised from that of freezing water (or melting ice) to that of boiling water. The actual blood temperature is now known to be 98.6° F. Its non-agreement with Fahrenheit's 100° blood temperature is due to errors in the original experiments.

Note.—The Centigrade Thermometric Scale (Fig. 69), or *Celsius scale*, as it is sometimes called, was invented by the Swedish physicist Celsius. The freezing and boiling temperatures of water were taken as definite limits of gradation. The height of the column of mercury at the freezing temperature was designated the zero-degree point of the scale. Also, the height of the mercury column at the temperature at which water boils was designated as the 100° point of the scale. The height of the mercury column between the freezing point and the boiling point was then divided into 100 equal spaces, each called a degree.

60. The Calibration Of A Centigrade Thermometer (Fig. 70) see also Sec. 659, consists in determining the 0°-mark by placing the thermometer in melting ice (Fig. 70, *I*) and marking the height of the mercury column when it is at that temperature. The thermometer is then placed in steam coming from boiling water (Fig. 70, *II*). The 100°-mark is placed even with top of the mercury when it is at the temperature of this steam. The distance between the 0°-mark and the 100°-mark is divided into 100 equal spaces. The rise of the

top of the mercury column for a distance equal to one space, indicates a temperature rise of one degree Centigrade (1° C.).

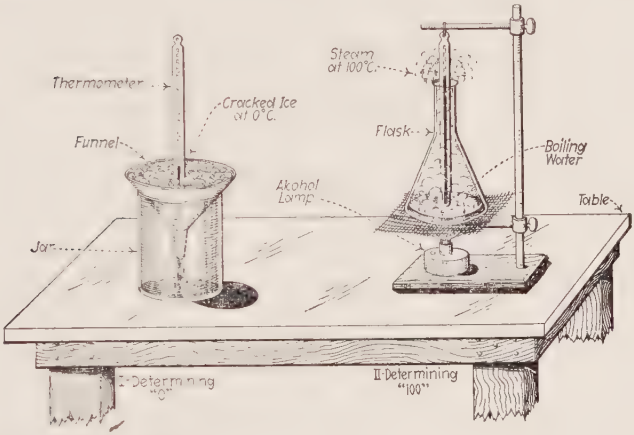


Fig. 70.—Determining 0 and 100-degree marks on a Centigrade thermometer.

61. The Absolute Thermometer Scale (Fig. 71) must be used in certain calculations concerning the thermal action of some substances, particularly gases. In order to describe this scale it is necessary to consider *absolute zero* (0° *abs.*) which is the lowest temperature theoretically attainable. It will be recalled (Sec. 52) that heat is a condition of motion of molecules. If it were possible to have a substance in such a state that the molecules were motionless, there certainly would be no kinetic heat energy in the substance and its temperature would then be the lowest possible to obtain. When a perfect gas, which is confined in a vessel, at 0° C. is cooled 1° C., its pressure is observed to decrease $\frac{1}{273}$ of the pressure at 0°. Since the pressure exerted by a gas is due to bombardment of the walls of the containing vessel by the vibrating

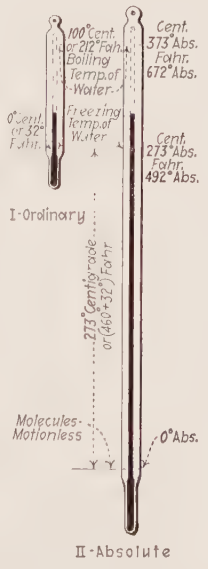

100° Cent. or 212° Fahr. Boiling Temp. of Water
Cent. 373° Abs. Fahr. 672° Abs.
0° Cent. or 32° Fahr. Freezing Temp. of Water
Cent. 273° Abs. Fahr. 492° Abs.
I-Ordinary
273° Centigrade or (460+32)° Fahr.
Molecules Motionless
0° Abs.
II-Absolute

Fig. 71.—Ordinary and absolute thermometer scales compared.

molecules, it is concluded from the above observation that if the temperature were lowered 273° C. below 0° C., there would then be no pressure exerted by the molecules. There would be absence of all heat. The temperature of a substance at this theoretically lowest temperature is assumed to be 0° *on the absolute scale.* The water freezing temperature is, then, 273° C. *abs.* (Fig. 71) and the boiling temperature of water is at 373° C. On the Fahrenheit scale, absolute zero is 492° *abs.* below the freezing point of water which is 32° F., hence, 0° F. is equivalent to 460° F. *abs.*

Note.—A Method Of Manufacturing A Thermometer (Fig. 72) follows: A glass tube with capillary opening and a bulb blown at one end (*I*) is filled with mercury. The bulb and contained mercury are heated (*II*) to a temperature somewhat higher than that for which the

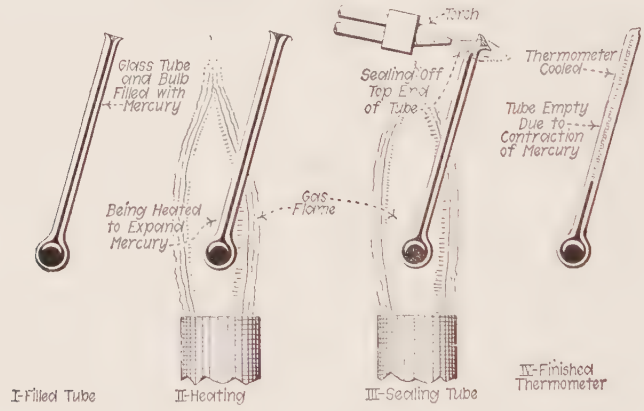


Fig. 72.—Steps in making a thermometer.

thermometer is to be used. While at this temperature the tube is sealed off—closed—(*III*) at its open end. When the tube, bulb, and mercury cool, the mercury contracts (*IV*) and leaves the tube empty in the upper portion. Thus, there is a vacuum above the mercury column.

62. Readings Of One Thermometer Scale May Be Converted To Equivalent Readings Of Another Scale.— It is often necessary in practice to make such conversions. Fig. 68 illustrates a thermometer with three scales, thus it is possible to read temperature from it in any one of the three, but usually thermometers are graduated for one scale only. Following

are facts and rules used for converting readings from one scale to another.

(16) $$1^\circ C. = \tfrac{9}{5}^\circ F. = 1.8^\circ F.$$

(17) $$1^\circ F. = \tfrac{5}{9}^\circ C. = 0.555^\circ C.$$

RULE 1.—TO REDUCE TEMPERATURES AS SHOWN ON THE FAHRENHEIT SCALE TO THE CENTIGRADE (Fig. 73), find the number of degrees

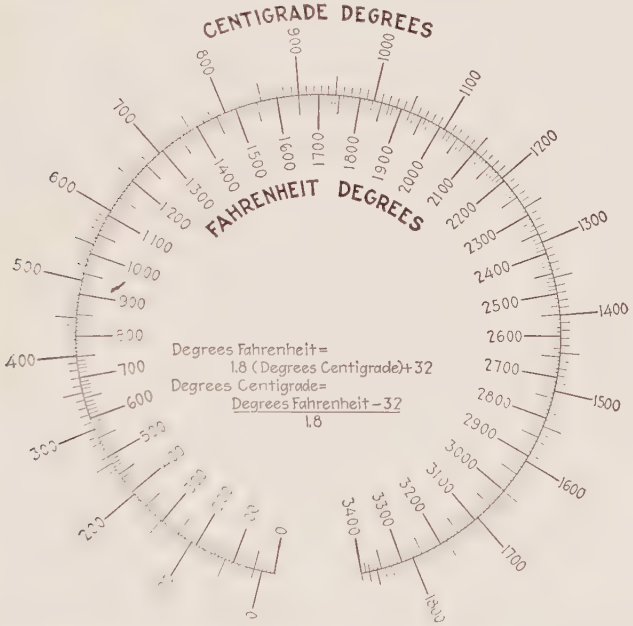


FIG. 73.—Chart showing relation of Fahrenheit to Centigrade degrees. (*W. S. Rockwell Company.*)

Fahrenheit above the freezing temperature of water and multiply by $\frac{5}{9}$. By formula:

(18) $$T_C = \tfrac{5}{9}(T_F - 32) \qquad \text{(deg. Cent.)}$$

Wherein: T_C = degrees on Centigrade scale. T_F = degrees on the Fahrenheit scale.

RULE 2.—TO REDUCE TEMPERATURES AS SHOWN ON THE CENTIGRADE SCALE TO THE FAHRENHEIT, multiply the numbers of degrees Centigrade by $\frac{9}{5}$ and add 32. By formula:

(19) $$T_F = \tfrac{9}{5}T_C + 32 \qquad \text{(deg. Fahr.)}$$

Wherein T_F and T_C have the same meanings as in For. (18).

Note.—To Convert A Thermometer Reading To Absolute Scale Centigrade, add 273 to the Centigrade reading. To convert a Fahrenheit reading to absolute temperature Fahrenheit, add 460 to the Fahrenheit reading. (The value 460 is not exact but is very nearly so.) These rules may be expressed by the following formulas:

(20) $\mathbf{T}_F = T_F + 460$ (deg. Fahr. abs.)

(21) $\mathbf{T}_C = T_C + 273$ (deg. Cent. abs.)

Wherein: $\mathbf{T}_F$ and $\mathbf{T}_C$ = the absolute temperatures measured in Fahrenheit and Centigrade degrees, respectively. T_F and T_C = respectively, the Fahrenheit and Centigrade temperatures.

Example.—A Fahrenheit thermometer records 180°. What is the equivalent Centigrade reading? Solution.—By For. (18), $T_C = \frac{5}{9}(T_F - 32) = \frac{5}{9} \times (180 - 32) = 82\frac{2}{9}°\ C.$

Example.—A Centigrade thermometer records 51 degrees. What is the equivalent Fahrenheit temperature? Solution.—By For. (19), $T_F = \frac{9}{5}T_C + 32 = [\frac{9}{5} \times 51] + 32 = 123\frac{4}{5}°\ F.$

Example.—The temperature of a solution (Fig. 74) is 20° *C*. What

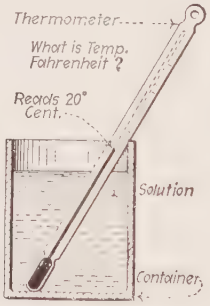


Fig. 74.—What is the Fahrenheit temperature?

would a Fahrenheit thermometer read in the same solution? Solution. By For. (19), $T_F = \frac{9}{5}T_C + 32 = [\frac{9}{5} \times 20] + 32 = 36 + 32 = 68°F.$

Example.—A certain solution solidifies at 9° below zero Fahr. (−9°F.) What is the equivalent temperature by a Centigrade thermometer? Solution.—By For. (18), $T_C = \frac{5}{9}(T_F - 32) = \frac{5}{9} \times (-9 - 32) = \frac{5}{9} \times (-41) = -22\frac{7}{9}°\ C.$, or $22\frac{7}{9}°$ *below zero Cent.*

Example.—A temperature of 32° F. is equivalent to 32 + 460 = 492° F. *absolute* (abbreviated *abs.*). A temperature of 550° F. is equivalent to 550 + 460 = 1,010° F. *abs.*

Example.—A certain solution at a certain pressure boils at 20° *C*. What is the absolute temperature in 8 degrees Centigrade at which the solution boils? Solution.—By For. (21), $\mathbf{T}_c = T_c + 273 = 20 + 273 = 293°\ C.\ abs.$

63. Table Showing Temperatures At Which Some Important Phenomena Occur.—The melting and boiling phenomena here listed occur at the temperatures shown only when the substances are heated at normal atmospheric pressure.

Temperature		Phenomena	Temperature		Phenomena
Deg. Cent.	Deg. Fahr		Deg. Cent.	Deg. Fahr.	
3,500	6,330	Temp. of electric arc.	288	550	Gunpowder ignites.
3,500	6,330	Carbon vaporizer.	215	420	Tin melts.
3,000	5,400	Attained by Thermit.	109	228	Sulphur melts.
2,800	5,072	Oxyacetylene flame.	100	212	Water boils.
2,500	4,532	Oxmium melts.	79	174	Alcohol boils.
2,225	4,037	Iridium melts.	65	149	Fusible alloy melts.
2,231	4,000	Bessemer furnace.	61	142	Beeswax melts.
1,710	3,080	Platinum melts.	46	114	Paraffin melts.
1,530	2,731	Wrought iron melts.	44	111	Phosphorous melts.
1,400	2,552	White "heat."	36.8	98	Human body in health.
1,371	2,500	Steel melts.	17	62	Mean temperature of sea.
1,200	2,192	Orange red "heat."	0	32	Water freezes.
1,100	2,012	Copper melts.	−17.7	0	Mixture salt and ice melts.
1,063	1,981	Pure gold melts.	−38.8	−34.3	Mercury freezes.
1,050	1,922	Cast iron (lowest) melts.	−55	−68	Temp. in Arctics.
970	1,778	Silver melts.	−70	−94	Balloon (9 miles high).
700	1,292	Dull red "heat."	−118	−180	Ether freezes.
625	1,157	Aluminum melts.	−252	−422	Hydrogen boils.
405	762	(About) coal ignites.	−259	−434	Hydrogen freezes.
400	752	Red hot iron visible in dark.	−270	−454	Greatest Artificial "cold" (1908).
357	674	Mercury boils.	−273	−460	Absolute zero.
316	600	Lead melts.			

64. Table Showing Equivalent Temperature Readings For Fahrenheit And Centigrade Scales.

Deg Fahr	Deg. Cent.	Deg. Fahr.	Deg. Cent.	Deg. Fahr.	Deg. Cent.	Deg Fahr.	Deg. Cent.
−40	−40	95	35	230	110	365	185
−31	−35	104	40	239	115	374	190
−22	−30	113	45	248	120	383	195
−13	−25	122	50	257	125	392	200
− 4	−20	131	55	266	130	401	205
5	−15	140	60	275	135	410	210
14	−10	149	65	284	140	419	215
23	− 5	158	70	293	145	428	220
32	0	167	75	302	150	437	225
41	5	176	80	311	155	446	230
50	10	185	85	320	160	455	235
59	15	194	90	329	165	464	240
58	20	203	95	338	170	473	245
77	25	212	100	347	175	482	250
86	30	221	105	356	180	491	255

QUESTIONS ON DIVISION 2

1. What is matter? How may it be recognized?
2. Name ten substances made of matter.
3. Of what is matter made up? Is this the smallest particle of matter?
4. What is an element? How many elements are known?
5. Name some common elements.
6. Of what is the atom composed?
7. Are atoms and molecules in contact? What holds them together?
8. What is the determining feature in the makeup of matter? What determines whether a substance is wood or iron?
9. Do molecules and atoms move? How?
10. How many times larger than a molecule of salt is the smallest particle that is visible under a microscope?
11. What is between atoms and molecules? Why no air?
12. Can matter be destroyed? Created?
13. In what three states is matter found? Describe briefly the condition of a substance in each state.
14. How do molecules behave in the three states?
15. Are molecules closer or further apart in a gas than in a solid?
16. What causes molecules to vibrate? What is heat?
17. What is temperature? Is the temperature an indication of the contained heat?
18. What is cold?

19. Is feeling a good way to judge temperature? Why?

20. How is temperature accurately measured?

21. Describe the Fahrenheit thermometer scale. The Centigrade.

22. What is the absolute thermometer scale? Explain.

23. What relation exists between Fahrenheit degrees and Centigrade degrees?

24. What is the rule for converting temperature readings on the Fahrenheit scale to the Centigrade scale? Vice versa?

25. How are ordinary thermometer readings reduced to absolute readings?

PROBLEMS ON DIVISION 2

1. Mercury boils at a temperature of 357° C. What is the equivalent temperature on the Fahrenheit scale?

2. Frozen ammonia is found to melt at −75.5° C. What is the equivalent temperature by a Fahrenheit scale?

3. Pure iron melts at about 2,750° F. What will a temperature recording instrument with a Centigrade scale record when inserted in the newly melted iron?

4. Hydrogen gas has been liquified at the very low temperature of −396.4° F. This is noticed to be near the temperature of absolute zero. What is the temperature by the Centigrade system of measuring temperature?

5. Express the following in absolute temperatures Fanrenheit: 212° F., 460° F., −32° F.

6. Express the following in absolute temperatures Centigrade: 100° C., 0° C., −175° C., 20° C.

DIVISION 3

THE SOURCE OF HEAT

65. Practically All Of The Earth's Heat Is Derived Either Directly Or Indirectly From The Sun.—It is this heat that insures continuance of all plant and animal life.

NOTE.—THE HEAT FROM THE SUN PROPAGATES PLANT LIFE UPON THE EARTH.—Eventually, the plants become available for use as fuel, either as coal (Fig. 75) or wood. Coal (Fig. 75) is formed from deposits of vegetable matter which have been subjected to great pressure and heat through long periods of time. Decay of vegetable and animal deposits within the earth also results in the formation of natural gas and mineral oil (Fig. 76). Such gas and oil are likewise available for fuel. The heat of the sun is stored up in these fossil fuels. Thus it is made indirectly available for mankind's use.

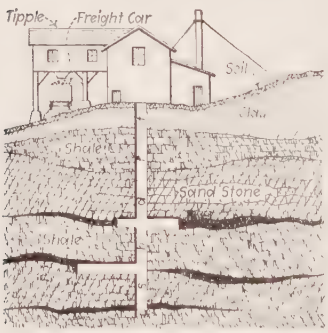


FIG. 75.—Section of a coal mine.

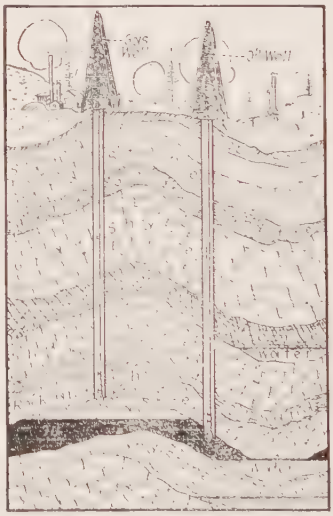


FIG. 76.—Section of earth showing gas and oil wells.

NOTE.—SMALL POWER PLANTS (Fig. 77) HAVE BEEN SO CONSTRUCTED AS TO DRAW THE HEAT NECESSARY FOR THEIR OPERATION FROM THE SUN.—But such plants are of very limited application. The power realized therefrom is, ordinarily, practically incommensurable with the

relatively great cost and complication of the apparatus required. Also, the direct heat of the sun is not constantly available. In some climates, long intervals may elapse during which the sun is obscured by clouds.

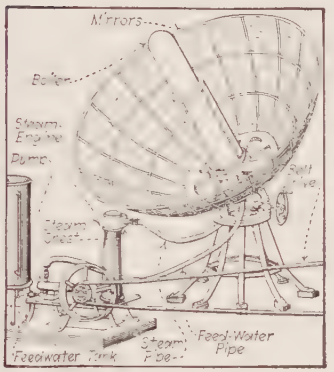


FIG. 77.

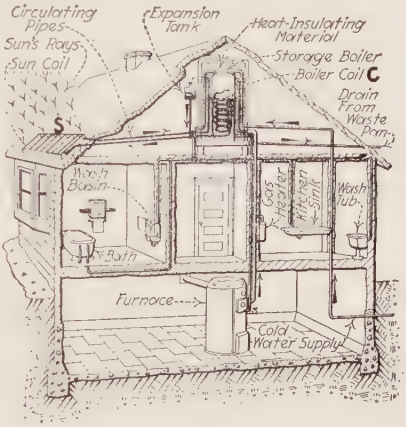


FIG. 78.

FIG. 77.—*Pifres* sun-power plant. (From *Smithsonian Report*, 1913.) (The mirrors are held in a reflector-shaped-frame unit which can be faced toward the sun. A hand wheel is used to rotate the unit to such a position that the sun's rays will fall directly on the mirrors. The rays from the sun then strike the mirrors and are reflected onto the boiler which is located in the center or "focus." The water in the boiler absorbs heat from the sun's rays and is thereby transformed into steam. The steam, thus formed, is used to drive the engine. The exhaust steam from the engine is used in a feedwater heater to heat the previously cold water which is pumped into the boiler.)

FIG. 78.—Showing installation for heating water for bathing and washing purposes. (*Day & Night Solar Heater Co.*, Los Angeles, Cal.) (The non-freezing liquid, shown in black, upon being heated in the sun coil, *S*, on roof, circulates through the coil, *C*, inside of the storage boiler, thus heating the water. Note that the warmed water, which is to be used, does not circulate through the sun coil, *S*.)

See also Fig. 78 which shows how the sun's rays are used directly for water heating in California.

66. Heat Rays From The Sun Cause Evaporation Of Water From Oceans, Lakes and Rivers.—The ascending vapors gather in the upper strata of the earth's atmosphere to form clouds. Eventually the vapors condense and descend again to earth, falling on hill and mountain in the form of rain. The rain flows in rivulets to larger streams and rivers. That water which falls on the higher parts of the earth's surface possesses potential mechanical energy. This may, with suitable equipment, be made available as mechanical or as electrical energy.

67. The Source Of Solar Heat has been investigated for many years. Several theories in explanation of its origin have been advanced. Probably the most satisfactory of these—the *nebular hypothesis*—is as follows:

Explanation.—It is assumed that the space now occupied by our planetary system was originally filled with a *nebula*. A nebula is believed by some to be an extremely tenuous body composed of unorganized gaseous matter whirling at an enormous speed around a common vortex or center. Others believe a nebula to be made up of *planetesmals* or particles of matter. Portions of this nebula separate from the parent mass. They gradually contract and cool during the course of ages. Eventually they formed the planets, planetoids, and other celestial bodies which comprise our present solar system of spheres—small and large—which revolve about the sun.

Coincidentally, the immense nebulous mass immediately adjacent to the vortex, or common center, (though extending thence in all directions through many millions of miles of space) was likewise contracting and solidifying into a compact body. This body is now known to us as *the sun*. The shrinking or contracting of the various portions of nebula has been due to the gravitational or attractive force of the particles which comprised the original mass.

68. The Contraction Of The Sun Converts Potential Energy Of Position Into Heat, just as the falling of a stone finally converts its potential energy of position into heat. It has been calculated that a contraction of the sun's diameter of about 250 ft. per year is sufficient to supply the heat which is given off by radiation. At this rate of contraction, 1,000 years would elapse before the sun would exhibit a sufficient alteration of size to be discerned through our telescopes. For a more complete discussion of this subject see Abbots' The Sun.

69. The Internal Heat Of The Earth Is Virtually Unutilized. The presence of this heat is evident from the volcanoes and hot springs that exist in certain localities. It is thought that the earth's crust may be 100 miles thick, and that beneath this crust the mass of the earth is molten hot.

Note.—The Earth's Internal Heat Is Utilized To Some Extent In Italy For The Development Of Power.—In certain volcanic regions powerful jets of superheated steam, of from 10,000 to 40,000 lb. per hr. capacity, and at pressures of from 30 to 75 lb. per sq. in., are obtained from borings in the earth. These borings are from about 8 to 16 in. in diameter and from 300 to 750 ft. deep. They are lined with steel

tubes which convey the steam to the earth's surface where it is utilized in steam engines, steam turbines or similar energy-converting equipment.

70. Mechanical Energy, or Action, Produces Heat.—It cannot be said that mechanical action is a source of heat, since the heat so produced comes indirectly from the sun. Heat is a *manifestation of certain mechanical action.* Or, otherwise stated, *mechanical energy may be converted into heat energy.* Primitive man found that he could start a fire (Fig. 79) by rubbing sticks together. The rubbing together of pieces of wood causes heat, due to the friction between the pieces. The mechanical energy applied by the man is transformed into heat energy. The man and the wood are dependent upon the sun for existence. Hence, the sun is, indirectly the source of the heat generated in the rubbing process.

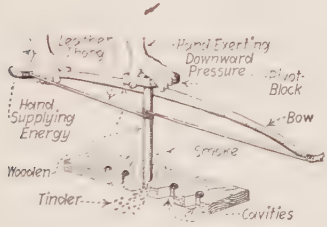


FIG. 79.—Fire from friction—kinetic energy transformed into heat energy.

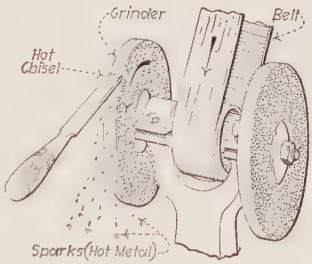


FIG. 80.—Heat from friction of chisel against moving grinder.

NOTE.—THE FORM OF FRICTIONAL HEAT THAT CHIEFLY CONCERNS THE POWER PLANT OPERATION is that which is manifested in the heating of engine and shaft bearings by reason of excessive load or inadequate lubrication.

EXAMPLES.—When an automobile, or a railway car, is stopped by applying the brake, considerable heat is developed by friction between the brake shoe and the wheel or other revolving element. The applied mechanical energy of the braking mechanism is converted into heat energy which is dissipated in the surrounding atmosphere. In grinding a tool (Fig. 80) on an emery wheel, or grindstone, heat is developed.

71. Heat Is Developed When The Physical Forms Of Bodies Of Matter Are Changed.—If mechanical energy is so applied as to change the shape of a body, heat is "generated." Lead becomes hot (Fig. 60) when hammered. The heat so manifested is due to percussion. When an iron wire (Fig. 59)

is bent continuously back and forth at the same point, it becomes hot because of the repeated changing of its shape. When a gas is confined in a cylinder (Fig. 34) and is compressed by the piston's forcing it into a smaller space, the gas becomes very warm. It may, under certain conditions, become sufficiently hot to ignite spontaneously. This *heat due to compression* is noticeable in the action of a bicycle or automobile tire-pump and in certain types of gas-engines (Fig. 34). It results from the decreasing of the volume occupied by the gas.

Note.—Heat Developed In The Compression Of a Gas Is Transmitted through the wall of the containing vessel and may be carried away in a current of water or in the surrounding atmosphere. Then re-expansion of the gas must be attended by absorption of a quantity of heat, from surrounding substances, equal to the quantity of heat so dissipated. This principle is utilized in the mechanical refrigerating plant. An often-observed example of the result of this phenomena is the coating of frost which forms on the end of a pneumatic-rock-drill exhaust pipe when the drill is in operation.

72. Heat May Be Derived From Electrical Energy.—That is, electrical energy may be transformed directly into heat energy. Every conductor which is carrying a current of electricity offers resistance to the current. A current-carrying conductor always becomes heated to some degree, even though the heating may often be practically inappreciable. Such heating of a conductor represents a loss of electrical energy. This

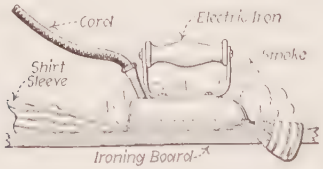


Fig. 81.—Heat from electrical energy.

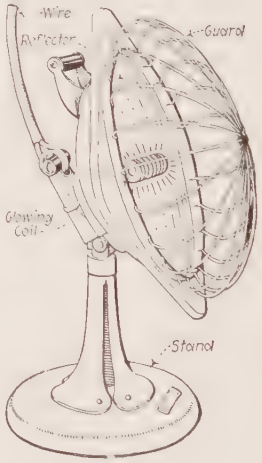


Fig. 82.—Heat from electrical energy.

loss is known to the electrician as the I^2R-loss, wherein I represents the current in amperes and R the resistance of the conductor in ohms.

Note.—The Heat Thus Developed In Electrical Conductors Is Made Useful In Various Ways.—Electric-furnaces, welding, car-heating, cooking, ironing (Fig. 81) are a few of the methods of utilizing electrically-developed heat. The electrical method of room heating (Fig. 82) offers many conveniences. It is, however, relatively expensive in most localities. Electricity, flowing through and heating to incandescence a metal filament, is now indispensable as a producer of light. While producing the light, the electric current also causes the white-hot incandescent-lamp filament to give off heat.

73. Heat Is Produced by Certain Chemical Reactions. That is, when certain chemical processes or reactions occur, chemical energy which resided in the substances involved in the reaction is transformed into and liberated as heat energy.

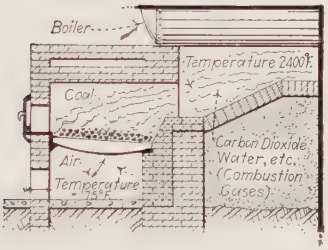


Fig. 83.—Combustion of coal—a chemical action.

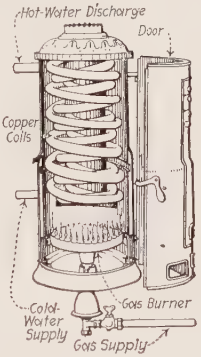


Fig. 84.—Combustion of gas heats water.

Conversely, it is necessary to add heat energy to effect certain other chemical reactions; see Sec. 157 for a further discussion. Chemical reaction includes all forms of combustion. And combustion—burning—of fuels is the source of heat with which the power-plant operator is mainly concerned. The combustion or burning of coal (Fig. 83), wood, oil or gas (Fig. 84), is the chemical action (see Div. 14 on Combustion) occurring between the carbon and hydrogen, contained in the fuel substances, and the oxygen of the air.

Note. The Respiration Of Animals Is a Process Of Slow Combustion Or Chemical Action. The oxygen breathed into the lungs combines with the carbon and other elements in the blood. The resulting chemical action liberates or "causes" *animal heat.*

74. The Elements Composing Fuel Substances Change Their Molecular Form In Uniting With Oxygen.—But nothing is lost (Sec. 48). Only the form is changed. This change is accompanied by a very violent action of the atoms in forming new molecules. It is so violent as to produce or liberate heat sufficient to cause the combustible substances to glow with a red or white light. This situation is explained more fully in Sec. 176. By combustion, the chemical energy (potential energy) of the fuel substance is converted into heat energy.

QUESTIONS ON DIVISION 3

1. What is mankind's main source of heat energy?
2. Why is the direct heat of the sun not commercially available as a source of power?
3. What is the relation between the sun's heat energy and the heat derived from the conbustion of wood?
4. What is the origin of natural gas?
5. How does the sun produce the power which may be realized from a waterfall?
6. Is the earth solid throughout? Explain.
7. Is the heat of the earth's interior available for producing power?
8. What causes the heating of an engine bearing? Is the heat due to friction in an engine bearing of any practical use in heating the room?
9. How does compression of a gas affect the temperature of the gas?
10. Name some uses of the heat which is always developed when an electric current flows in a conductor.
11. Explain how heat is developed by the combustion of fuels.
12. What transformation of energy occurs when coal burns?

DIVISION 4

HEAT—ITS MEASUREMENT AND TRANSFORMATIONS

75. The Amount Or Quantity Of Heat Which Any Portion Of Matter Contains is determined by: (1) *The weight of the portion of matter.* (2) *The nature of the substance.* (3) *Its condition, whether solid, liquid, or gaseous.* (4) *Its temperature.* (5) *Its pressure,* if the substance is a gas. Therefore, if the condition and characteristics, as specified in the five preceding items, are known, concerning a body, the quantity of heat which it contains can, as will be shown, be determined.

76. For Measuring Quantity Of Heat A Unit Is Necessary.—The ancient philosophers thought that heat was a fluid. Heat does resemble a subtle fluid, in that it may be "poured into" a portion of matter to make it warmer, or "drawn out" of the body to cool it. Just as the gallon is the unit for measuring quantity of water, so the British thermal unit (which is defined in the following section) is a unit by which quantity of heat may be measured. But it should be remembered that heat is by no means a fluid. It is (Sec. 32) kinetic molecular energy.

77. A Unit For Measuring Quantity Of Heat Is The "British Thermal Unit" (B.t.u.).—A definition, sufficiently accurate for practical purposes, is this (Fig. 85)—*A British thermal unit is the amount or quantity of heat, required to increase the temperature of 1 lb. of water, 1° F.* The preceding interpretation is the one which will be assumed in this book, unless otherwise specified.

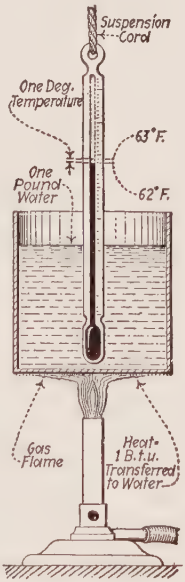


FIG. 85.—One B.t.u. = quantity of heat required to raise 1 lb of water 1° F

Note.—To Define The B.t.u., With Scientific Accuracy, the temperature range must be specified definitely. The usually-accepted technical definition is: *A B.t.u. is the amount of heat required to raise the temperature of 1 lb. of water from 62° F. to 63° F.* Certain authorities specify the lower temperature as 15° C. (59° F.), while others specify 39.1° F., at which temperature water has its maximum density. Another definition states that "a B.t.u. is $\frac{1}{180}$ of the total heat required to raise the temperature of 1 lb. of water from the freezing to the boiling point." Due to the fact that experiments show that the heat actually required to raise the temperature of water 1° F., varies with the temperature of the water, it is essential, in precise laboratory determinations, that the unit be defined accurately. But the technicalities introduced in the different definitions, given in this note, can be disregarded in practical engineering.

78. The Formula For Computing The Amount Of Heat Required To Change The Temperature Of Water A Specified Degree Is:

(22) $\mathbf{Q} = \mathbf{W}(T_2 - T_1)$ (British thermal units)

Wherein: $\mathbf{Q}$ = amount of heat added or subtracted, in British thermal units. $\mathbf{W}$ = weight of water, in pounds. T_1 and T_2 = respectively, upper and lower temperatures, in degrees Fahrenheit.

Derivation.—Since by definition, 1 B.t.u. will increase the temperature of 1 lb. of water 1° F., it is merely necessary, in order to determine the heat required to increase the temperature of the water any number of degrees Fahrenheit, to multiply the weight of water, under consideration, by the rise, in temperature which occurs, in degrees Fahrenheit. This operation is the one which the formula specifies.

Example. How much heat is required to raise the temperature of 1 gal. of water from 75 to 101° F.? Solution.—A gallon of water weighs 8.3 lb. Substituting in For. (22): $\mathbf{Q} = \mathbf{W}(T_2 - T_1) = 8.3(101 - 75) = 216$ *B.t.u.*

79. The Small Calorie Is The Metric Unit Of Quantity Of Heat.—The *small calorie* is used almost exclusively in physical-laboratory work, the world over. The small calorie is the amount of heat required to raise the temperature of 1 gram (1 cubic centimeter) of water 1° C

(23) 1 *B.t.u.* = 252 *small calories.*

(24) 1 *small calorie* = 0.004 *B.t.u.* (*approximately*)

Note.—The Kilogram Calorie, Or Large Calorie, is one thousand times as great as the small calorie. It is used in engineering computations in countries which have adopted the metric system.

(25) 1 *B.t.u.* = 0.252 *large calorie.*
(26) 1 *large calorie* = 3.968 *B.t.u.*

NOTE.—WHERE HEAT QUANTITY IS SPECIFIED IN CALORIES, it should be designated whether the *large calorie* or the *small calorie* is implied.

EXAMPLE.—How many small calories are equivalent to 615 B.t.u.? SOLUTION.—Now, 1 B.t.u. = 252 small calories. Therefore, 615 *B.t.u.* = 615 × 252 = 154,980 *small calories.*

EXAMPLE.—How many B.t.u. are required to raise 5 kilograms of water 5° C. in temperature? SOLUTION.—It is a fact that: 5 *kilograms* = 5,000 *grams.* Hence, *heat required to raise* 5,000 *grams,* 5° *C.* = *gm.* × *deg. Cent.* = 5,000 × 5 = 25,000 *small calories.* Now, 1 *small calorie* = 0.004 *B.t.u.* Therefore, 25,000 *cal.* = 25,000 × 0.004 = 100 *B.t.u.*

80. The First Law Of Thermodynamics is: *Heat and mechanical energy can be converted one to the other and, when thus converted, a definite relationship always exists.* This follows from the statements of Secs. 25 and 26. It means that heat energy can be transformed into mechanical energy (Fig. 86) and, conversely, that mechanical energy can be converted to heat energy; it means, further, that for each unit (1 B.t.u., for example) of heat energy that is converted into mechanical energy, a certain number of mechanical-energy units (foot-pounds) will be formed, and vice versa. The original number of energy units of one kind of energy determines the number of energy units of the other kind that will result from a perfect conversion. See following sections.

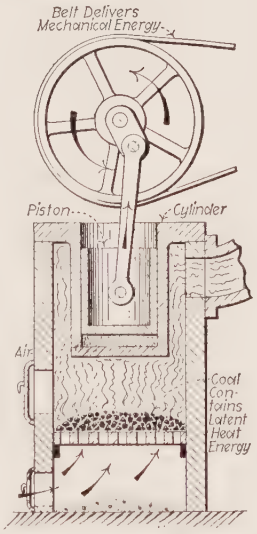


FIG. 86.—Heating a confined gas in a hot-air engine increases the volume of the gas and thereby converts heat into mechanical energy.

81. Since "Heat And Mechanical Energy May Be Converted From One To The Other" There Must Obviously Be A Mechanical Unit Equivalent Of The British Thermal Unit.—The foot-pound (Sec. 22) is a unit of mechanical energy. The B.t.u. is a unit of heat energy. It follows, therefore, that a B.t.u. should be equivalent to a certain definite number of foot-pounds. Experiments have proven that it is.

82. The Mechanical Equivalent Of Heat, that is, *the number of foot-pounds in a B.t.u.* has been determined and verified thousands of times. The principle of the apparatus involved is explained below. All of these experiments show that for practical engineering purposes.

(27) $1\ B.t.u. = 778\ ft.\text{-}lb.$

(28) $1\ ft.\text{-}lb. = 0.001{,}28\ B.t.u.$

(29) $1\ hp. = 42.42\ B.t.u.\ per\ min.$

(30) $1\ hp. = 2{,}545\ B.t.u.\ per\ hr.$

Note.—Precise Determinations Of The Mechanical Equivalent Of Heat by the *United States Bureau of Standards* indicate that: **1** *B.t.u.* = 778.2 *ft.-lb.*, when 1 B.t.u. is taken as the heat necessary to raise the temperature of 1 lb. of water from 59 to 60° F., and = 777.5 *ft.-lb.* when the B.t.u. is measured at 62° F. A B.t.u. is often taken as equal to 778 ft.-lb., as stated above. The arrangement used for determining the mechanical equivalent of heat (Fig. 87) provides for the meas-

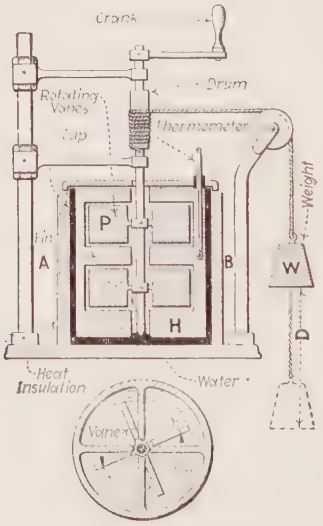


Fig. 87.—Apparatus for determining mechanical equivalent of heat.

uring of the heat energy imparted to a known weight of water, *H*, by the foot-pounds of work done on the water, through the action of submerged paddles, *P*, which are caused to rotate by a falling weight, *W*. See also Figs. 88 and 89 for another arrangement for determining the mechanical equivalent of heat.

Explanation.—The foot-pounds of work done by W (Fig. 87), in falling a distance D is (neglecting friction, which can be rendered insignificant) expended solely in stirring the water H. The friction produced

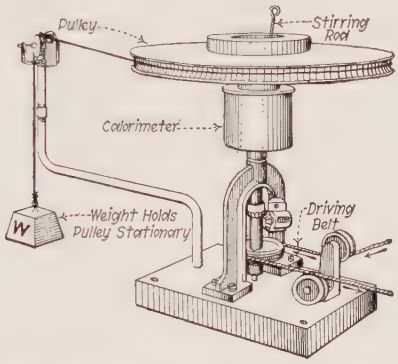


Fig. 88.—Mechanical equivalent of heat apparatus. (*Central Scientific Co.*) See succeeding illustration. The falling weight does work—expends energy—which heats the water in the container.

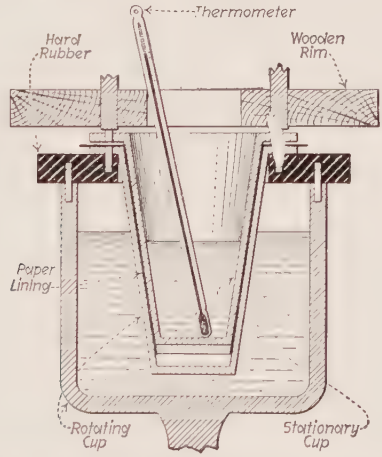


Fig. 89.—Section of friction element of mechanical equivalent apparatus. (This is a partial sectional view of the equipment shown in the preceding illustration.)

thereby raises the temperature of the water. This indicates that heat has been imparted to the water. By noting the rise in temperature and the weight of water, the amount of heat energy which results from the expenditure of the mechanical energy may be calculated readily.

Example.—Water weighing 125 lb. and at 60° F. is held in a container, like that of Fig. 87. It is stirred by the paddles which are actuated by a

falling weight, which, when the temperature of the water has attained 63° F., has developed 291,750 ft.-lb., of work. Assuming that all exterior friction is negligible, how many foot-pounds does each B.t.u. of heat, imparted to the water, represent. Solution.—Heat absorbed by the water, For. (22) $= Q = W\ (T_2 - T_1) = 125 \times (63 - 60) = 125 \times 3 = 375$ *B.t.u.* Then the *foot-pounds expended per B.t.u.* $= 291{,}750 \div 375 = 778$ *ft.-lb.*, which is the mechanical equivalent of heat as specified above.

83. The Mechanical Equivalent Of Heat May Be Determined Electrically with an apparatus (Fig. 90) whereby the electrical energy is expended in a resistor which is submerged in a vessel containing a known weight of water. The watthours energy expenditure can be reduced readily to foot-pounds. (It is a fact that: 1 *watt-hour* = 2,655.4 *ft.-lb.*) Then, knowing the initial and final temperatures of the water, the mechanical equivalent of heat can be determined.

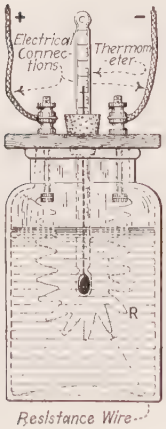


Fig. 90.—Electrical calorimeter for determining heating effect of electric current.

84. The Second Law Of Thermodynamics may be stated in many ways; two statements of the law are given here: (1) *Heat has never been known to flow of its own accord from a cold to a relatively hotter body.* (2) *It is impossible to obtain work by cooling any portion of matter below the temperature of the coldest of surrounding objects.* To cause heat to flow from a cold to a relatively hotter body (as it does in refrigerating machines) an expenditure of energy is required. The consequences of this law are of great importance. It will be shown by means of this law that heat can never be completely converted into mechanical energy—not even under ideal conditions. Whenever heat energy is converted into mechanical energy, some of the heat must remain in the unconverted state as heat energy. The heat which cannot be converted may be considered as an unavoidable "loss," although the heat is not actually lost.

Example.—Much of the heat of the steam from a boiler may be unavoidably "lost" (Fig. 91) by radiation from the pipes and through

the exhaust from the engines. But this "lost" heat raises the temperature of the surrounding atmosphere, and is absorbed therein.

NOTE.—THE FLOW OF HEAT IS SIMILAR TO THE FLOW OF WATER. If temperature be thought of as a sort of "head" or vertical distance, then certain heat phenomena become very clear. Thus, it is known to everyone that water will not, of its own accord, flow uphill. Statement (1) above is very similar. Likewise, it may be said that it is, in general, impossible to obtain work from a stream of water by allowing the water to flow to an elevation lower than that of the height of the lowest nearby natural stream. This is shown by Fig. 92. In *II*, Fig. 92, the centrifugal pump will be found to require more power than is gained by using Arrangement *II* instead of Arrangement *I*. This idea is similar to that of statement (2) above.

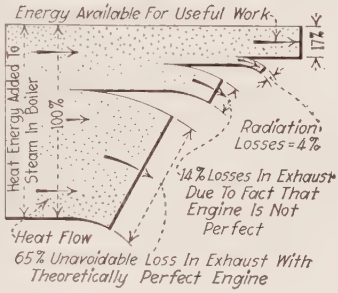

Energy Available For Useful Work
17%
Heat Energy Added To Steam In Boiler
100%
Radiation Losses = 4%
14% Losses In Exhaust Due To Fact That Engine Is Not Perfect
Heat Flow
65% Unavoidable Loss In Exhaust With Theoretically Perfect Engine

FIG. 91.—Diagram showing distribution of energy in a non-condensing steam plant (values are typical but approximate only).

NOTE.—THE SECOND LAW OF THERMODYNAMICS CONTRADICTS THE POSSIBILITY OF PERPETUAL MOTION.—If heat could be taken from the

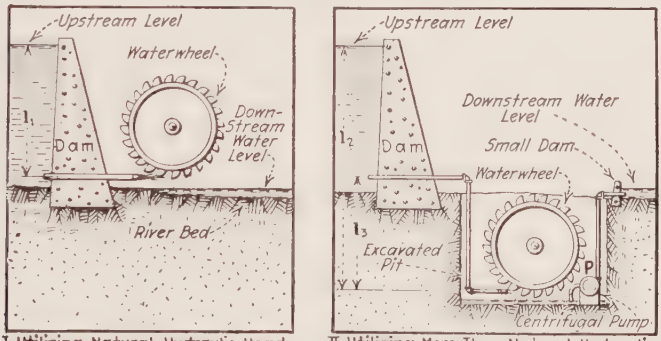


FIG. 92.—Illustrating the second law of thermodynamics. The head, l_2, in *II* is greater by the distance l_3, than that, l_1, in *I*. But nothing is gained in *II* by increasing the head by l_3 because the water has to be pumped back up again to the "elevation of the lowest nearby natural stream" so that it can flow away. In fact arrangement *II* would actually be considerably less efficient than that of *I* because of the losses in the additional piping and in the centrifugal pump *P*. This pump would have to be driven by the water wheel.

atmosphere, which contains an almost unlimited supply of heat, and could be converted into work, then it would be possible to derive mechanical energy without the expenditure of chemical energy, as from a fuel.

But, as stipulated by the second law—statement (2) above—it is impossible to obtain work from the atmosphere, or from anything else, by cooling it below the temperature of the coldest surrounding objects. Now, the temperature of the atmosphere is a sort of sea-level of temperature—it is the temperature to which all bodies either hotter or colder will ultimately come if left to themselves. To obtain work from a hydraulic motor or waterwheel, there must be a head of water; that is, there must be a decrease of altitude down to a lower level. Likewise, to obtain work from a heat motor, there must be a fall of temperature and this requires a source of heat at a temperature higher than atmospheric. Or, using the atmosphere as a heat source, there would be required a refrigerator, or cooling medium, at a temperature lower than that of the atmosphere. The latter alternative is impossible, for there cannot be found in nature any portion of matter which is permanently colder than the atmosphere and which can be used as a refrigerator. Hence, it is impossible to obtain work from the heat in the atmosphere.

85. The Conversion Of Heat Energy Into Mechanical Energy Can Never Be Complete.—Theoretically, it would be possible to completely convert heat energy into mechanical energy *if a substance were found whose temperature is absolute zero* (Sec. 61). But since, as stated in the preceding note, no substance can be found the temperature of which is permanently lower than that of the atmosphere, every transformation of heat energy into mechanical energy, even though the machine is frictionless, will involve a loss due to *rejected* or *degraded heat* which *cannot* be transformed into mechanical energy.

An Example Of This Degraded Heat is the heat in the exhaust of a steam engine, steam turbine, or internal-combustion engine. This degraded heat energy is comparable to the potential energy in the water which is discarded by a hydraulic motor or waterwheel—the discarded water is still about 3,950 miles from the center of the earth and therefore still contains a great amount of potential energy. But this energy cannot be utilized in a waterwheel because the waterwheel must discard its water into a nearby stream. Hence no waterwheel utilizes, or converts into useful mechanical energy, all of the potential energy in its water supply.

86. The Conversion Of Mechanical Energy Into Heat Energy Usually Is Complete.—Compare this with the opening statement of the preceding section. If a brake be applied to a turning wheel, all of the mechanical energy (which is consumed in overcoming the resistance of the brake) will be transformed into heat—which will raise the temperature of the brake, wheel

and surrounding objects and air. In fact, the apparatus for determining the mechanical equivalent of heat (Figs. 87 and 88) is based on this principle. This may again, as in the preceding section, be likened to the conversion of work into potential energy when work is done in lifting water. If 1 lb. of water is raised 1 ft. from the surface of the earth, its potential energy will be increased by 1 ft.-lb. All of the work done on the water adds to its stock of potential energy.

87. The "Thermal Capacity" Or "Heat Capacity" Of A Substance Is the quantity of heat (number of heat units) that under chosen conditions, must be added to or subtracted from the substance to change its temperature one degree. In the English system, the thermal capacity is the number of British thermal units which must be imparted to or abstracted from the substance to change its temperature 1° F. The thermal capacity of a given substance need not always be the same. It depends on the state (Sec. 49) of the substance and often on many other things.

Examples.—If a gas be heated in a container of given volume, its thermal capacity will be different than if the gas is heated in a container where it can expand—as when it forces out a piston; see following Sec. 99. For solids and liquids the thermal capacity varies slightly with the temperature (Sec. 88) but the variation is so small that, in engineering work, it is generally neglected.

88. The "Specific Heat" Or "Coefficient Of Thermal Capacity" Of A Substance is its thermal capacity (Sec. 87) per unit mass. It is the number of British thermal units that must be imparted to, or abstracted from, each *pound* of the substance to change the temperature of the substance 1° F. Just as the thermal capacities of different substances depend on the conditions under which they are heated or cooled (Sec. 87), so do also the specific heats of different substances. Figs. 93 and 94 show how the specific heats of water, carbon, and iron vary with the temperature. The specific heat of a gas may, as is explained in Div. 8, have almost any value depending on the conditions under which the gas is heated or cooled.

Note.—The Exact Definition Of Specific Heat is: *The specific heat of a substance, at a given temperature and under given external conditions, is the ratio of the thermal capacity per unit mass of this substance, at*

the given temperature and under the given conditions, to the thermal capacity per unit mass of water under some chosen standard temperature and external conditions If the chosen temperature and pressure for water are 63.5° F. and atmospheric pressure, then the thermal capacity of the water per unit mass is 1 and the specific heat of the substance becomes numerically

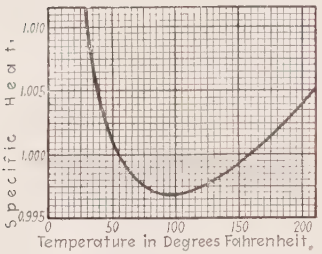


Fig. 93.—Specific heat of water at different temperatures and at saturation pressure. (Marks & Davis *Steam Tables.*)

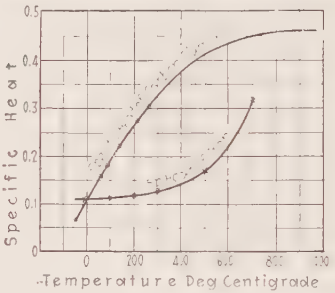


Fig. 94.—Specific heats of carbon and iron at different temperatures. (Franklin and McNutt.)

equal to its thermal capacity per unit mass under the given conditions. Thus, a specific-heat value is a ratio. It merely expresses how much heat is required to raise the temperature of *any* weight of the substance by 1° as compared with the heat required to raise the temperature of *the same weight of water* by 1°.

Note.—A Specific Heat Value Is Not Properly Nor Necessarily Expressible In Any Certain Unit.—There is only one specific-heat value for a given substance (See Table 90) and given conditions. This value holds regardless of what units of weight, temperature, and heat measurement are employed. In this respect, a specific heat value for a given substance is similar to a specific-gravity value.

89. Different Substances Have Different Specific Heats.—This truth may be verified by dropping two heated balls, one of copper and one of iron, each weighing 1 lb., and at the same temperature, into two vessels, both of which contain the same weight of water, at the same temperature. It will be found that the water in the vessel in which the iron ball is dropped attains the higher temperature. This shows that a pound of iron, at a given temperature, contains more heat than a pound of copper at the same temperature.

Example.—Water has (by definition of the B.t.u., Sec. 77), a specific heat of 1.0. It has the greatest specific heat or capacity for heat of any common substance. For the specific heats of various substances, see Table 90.

90. Table Showing Mean Specific Heats Of Substances Between The Temperatures Of 32 And 212° F. (These values, except those shown for gases, are all at constant atmospheric pressure.)

Substance	Specific heat	Substance	Specific heat
SOLIDS: PURE METALS			
Aluminum	0.218	Marble	0.21
Antimony	0.051	Paraffin wax	0.69
Calcium	0.170	Porcelain	0.255
Copper	0.093	Sand	0.195
Gold	0.031	Wood, *Oak*	0.57
Iron	0.110	Wood, *Pine*	0.67
Lead	0.031	LIQUIDS	
Nickel	0.108	Acetic Acid	0.51
Platinum	0.032	Alcohol	0.70
Silver	0.056	Benzol	0.43
Tin	0.055	Ether	0.503
Tungsten	0.034	Gasoline	0.70
Zinc	0.094	Glycerine	0.576
SOLIDS: VARIOUS ALLOYS		Kerosene	0.50
		Machine oil	0.40
Bell metal	0.086	Mercury	0.033
Brass, yellow	0.088	Petroleum	0.033
Brass, red	0.090	Sulphuric acid	0.498
Bronze	0.104	Turpentine	0.472
German silver	0.095	Water	1.000
Nickel steel	0.109	MOLTEN METALS	
Solder	0.04 to .045	Lead 590°–680°	0.041
Type metal	0.039	Tin 460°–660°	0.058
SOLIDS: MISCELLANEOUS			
Asbestos	0.20		
Ashes	0.20		
Brick	0.22		
Carbon, coke	0.203		
Cinders	0.18		
Coal	0.314	GASES AT 62° F.	
Concrete	0.27		Constant pressure / Constant volume
Cork	0.485	Air	0.238 / 0.169
Glass, *Normal*	0.198	Oxygen	0.217 / 0.155
Glass, *Crown*	0.16	Nitrogen	0.247 / 0.176
Glass, *Flint*	0.12	Hydrogen	3.420 / 2.440
Granite	0.195	Carbon monoxide (CO)	0.243 / 0.172
Ice	0.504	Carbon dioxide (CO_2)	0.210 / 0.160
India rubber	0.27 to 0.48	Sulphur dioxide (SO_2)	0.154 / 0.123
Limestone	0.217	Ammonia (NH_3)	0.523 / 0.407
		*Steam (average	0.452 / 0.347

* For one condition only. See also Table 394

91. The Formula For Determining The Specific Heat Of A Substance On The Basis Of Its Weight And Temperature Change follows from the definition of Sec. 88. It is there implied that *specific heat = B.t.u. per pound per degree temperature difference.* Note, Sec. 93 below, that this applies only when there is no change in state.

$$C = \frac{Q}{W(T_2 - T_1)} \qquad \text{(specific heat)} \tag{31}$$

Wherein: **C** = specific heat of the substance. **Q** = total heat added to the substance, in B.t.u. **W** = weight of the substance, in pounds. T_1 = temperature before **Q** is added, in degrees Fahrenheit. T_2 = temperature after **Q** is added, in degrees Fahrenheit.

Example.—A certain mixture, weighing 10 lb., requires 7.5 B.t.u. to raise its temperature 1° F. What is the specific heat of the mixture? Solution.—Substituting, For. (31): $C = Q \div [W(T_2 - T_1)] = 7.5 \div [10 \times 1] = 0.75$ = *specific heat of the mixture.*

92. The Formula For Computing The Amount Of Heat That Must Be Added To A Substance Of Known Specific Heat To Increase Its Temperature A Certain Degree Or The Heat Which Must Be Abstracted To Cool A Body A Certain Degree (when there is no change in state, Sec. 93 below) is obtained by transposing For. (31) thus:

$$Q = CW(T_2 - T_1) \qquad \text{(British thermal units)} \tag{32}$$

Wherein the symbols have the same meanings as specified above.

Example.—The specific heat of a certain grade of coal is known to be 0.31. How many B.t.u. of heat will be required to raise the temperature of 1.5 lb. of this coal from 61 to 67° F.? Solution.—Substituting, in For (32): $Q = CW(T_2 - T_1) = 0.31 \times 1.5 \times (67 - 61) = 2.79$ *B.t.u.*

93. The Above Formulas Apply Only Where There Is No Change Of State (Sec. 49). This refers to Formulas (31) and (32). If heat is added to water under atmospheric pressure, and at a temperature of 212° F., it will be found that many heat units must be added to change the temperature. Water changes into steam —changes its state—at 212° F. Much additional heat (Sec. 106) is required to effect the change. After water vaporizes into steam its specific heat

changes; see Table 90. Also, after water freezes into ice—changes from the liquid to the solid state—its specific heat is different. In fact, the doctrine just outlined, applies in general to all substances, as will be evident from a consideration of the specific heat values of Table 90.

94. To Determine The Specific Heats Of Solid Substances, The Method Of Mixtures is, ordinarily, the most practicable. A special container (Fig. 95) is employed to hold the liquid—usually water—and the solid while they are being mixed. The container is, frequently, nickel plated (Sec. 144) or lagged (Fig. 96) with

Fig. 95.—Simple calorimeter.

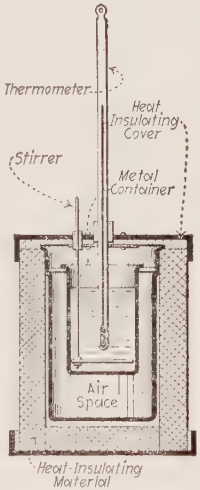


Fig. 96.—Calorimeter assembled (*Central Scientific Company*).

heat-insulating material (Sec. 114) to minimize the ingress or egress of heat during the determination. Such a container is called a *calorimeter*. Since nearly all heat measurements are made in calorimeters, heat measurement is often termed calorimetry. The formula employed in computing the specific heat—its derivation and an explanation are given below—is:

$$C_H = \frac{C_C W_C (T_M - T_C)}{W_H (T_H - T_M)} \quad \text{(British thermal units)} \tag{33}$$

Wherein: C_H = the specific heat of the hotter body. W_C = the weight of the cooler body, in any weight unit whatsoever. C_C = the specific heat of the cooler body; if water is used for the cooler body this specific heat will be "1." T_M = the final temperature of the mixture, in any temperature unit

whatsoever. T_C = the original temperature of the cooler body expressed in the same temperature unit as T_M. W_H = the weight of the hotter body, expressed in the same weight unit as W_C. T_H = the original temperature of the hotter body, expressed in the same temperature unit as T_M.

Derivation.—In the method of mixtures, the cooler body absorbs heat and the hotter body looses heat. Obviously, the amount of heat gained by the cooler body must equal the amount of heat lost by the hotter body. This must be true since the calorimeter is so constructed that no heat can enter or leave it during the determination. Also, it is an obvious fact that the originally-cooler body and the originally-hotter body must finally attain exactly the same temperature in the calorimeter, which temperature is herein designated by T_M. Now, from For. (32), the heat gained by the cooler body will be:

(34) $$Q = C_C W_C (T_M - T_C)$$ (British thermal units)

Also, from For. (32), the heat lost by the hotter body will be:

(35) $$Q = C_H W_H (T_H - T_M)$$ (British thermal units)

Since the heat gained by the cooler body, as expressed by For. (34), must equal the heat lost by the hotter body, which is expressed by For. (35), it follows that:

(36) $$C_C W_C (T_M - T_C) = C_H W_H (T_H - T_M)$$

Now, assuming that it is desired to solve for the specific heat of the hotter body, by transposing For. (36) there results:

(37) $$C_H = \frac{C_C W_C (T_M - T_C)}{W_H (T_H - T_M)}$$ (specific heat)

which is the same as For. (33).

Example.—What is the specific heat of lead? The lead weighs 3 lb. The water in the calorimeter (Fig. 97) weighs 4 lb. The temperature of the lead, before immersing in the water was 210° F. The initial temperature of the water in the calorimeter was 55° F. The maximum temperature of the water-lead mixture in the calorimeter, after adding the hot lead, is 58.47° F. Solution.—Substituting in For. (33): $C_H = C_C W_C (T_M - T_C)/W_H (T_H - T_M) = [1 \times 4(58.47 - 55)] \div [3(210 - 58.47)] = 13.88 \div 454.59 = 0.031$.

Explanation.—It Is Desired (Fig. 97) To Determine The Specific Heat Of Lead. All that are necessary are: (1) *Some pure water.* (2) *Lead shot.* (3) *Two thermometers.* (4) *Calorimeter.* (5) *A method of heating the lead.* First, pour a known weight of water (say 4 lb.), which should be at about room-temperature, into the calorimeter. Determine accurately the temperature of this water (say it is 55° F.). Now pour the shot into a container, a test tube will do. Then lower the test tube and shot (say 3 lb.) into, and permit them to remain in a vessel of hot water until the shot become heated to some certain observed temperature, say 210° F.

Next, the 210° F. shot are poured from the test tube into the water in the calorimeter, which should contain a thermometer. The temperature of this water will be observed to increase considerably due to the heat flowing from the hot shot into the water. Note the maximum temperature which the water attains (say it is 58.47° F.).

Now, obviously, the temperature of the lead has decreased. The temperature of the water has increased. Since the weight of the water in the calorimeter and its temperature rise are known, the B.t.u. of heat imparted to it by the shot may be computed by applying For. (32). This heat in B.t.u. (imparted to the water by the shot) must be the same amount of heat as that which is given up by the lead. Then, since the temperature in degrees, the weight, and the amount of heat given by the lead to the water are known, the specific heat of the lead may be determined, readily, by using For. (32) transposed. Study the following solution, of the example above given, in which it is assumed that there are no heat losses to the air or to the calorimeter and its insulating material. This solution illustrates another slightly different method of calculating specific heat. In a practical problem, the heat-loss items would require consideration, if accurate results are essential.

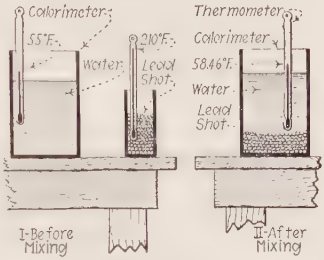


FIG. 97.—Determining specific heat of lead by the "method of mixtures."

SOLUTION.—By For. (32) *the heat imparted to the water* = $Q = C \times W(T_2 - T_1) = 1 \times 4\ (58.47 - 55) = 13.88$ *B.t.u.* Therefore, also *the heat given up by the lead* = 13.88 B.t.u. That is, *the heat lost from the lead = heat gained by the water.* Then, $Q = C_H W_H(T_H - T_M)$ or $C_H = Q \div [W_H(T_H - T_M)] = 13.88 \div [3(210 - 58.47)] = 0.031$, which is the specific heat of lead, as shown in Table 90.

95. The Effect Of Mixing Two Or More Different Substances Of Unequal Temperatures may be understood from a further consideration of the principles which have just been presented. Thus, if 10 lb. of water at 20° F. is mixed with 10 lb. of water at 100° F., obviously, the resulting temperature of the mixture will be: (20 + 100) ÷ 2 = 60° F. However, if 10 lb. of water at 20° F. is mixed with 10 lb. of copper at 100° F., the temperature after mixing will not be 60° F. The resulting temperature can—if there is no change of state, Sec. 93, as a result of the mixing—be computed by using this formula:

$$(38)\quad T = \frac{W_1C_1T_1 + W_2C_2T_2 + W_3C_3T_3 + etc.}{W_1C_1 + W_2C_2 + W_3C_3 + etc.} \qquad \text{(degrees)}$$

Wherein: W_1, W_2, W_3, *etc.* = respectively, the weights of the different substances of the mixture, in any weight unit whatsoever providing all are in the same unit. C_1, C_2, C_3, *etc.* = respectively, the corresponding specific heats of the different substances. T_1, T_2, T_3, *etc.* = respectively, the corresponding initial temperatures of the different substances, in any temperature unit provided all are in the same unit. T = the resulting final temperature of the mixture, in the same temperature unit as T_1, T_2, T_3, *etc.*

Derivation.—Temperatures as shown by thermometer scales are reckoned above an arbitrary datum or "zero." Now, by definitions: *The heat in a substance above the arbitrary zero = Weight × Specific heat × Temperature above* 0°. That is, using symbols, the heat, **Q**, in a substance above 0° may be expressed by:

(39) $$Q = WCT \qquad \text{(heat)}$$

or by transposing For. (39), the temperature, T, of a substance of known weight, **W**, known specific heat, **C**, and to which has been added a known quantity of heat, **Q**, will be:

(40) $$T = \frac{Q}{WC} = \frac{\textit{Quantity of heat above } 0°}{\textit{Weight} \times \textit{Specific heat}} \qquad \text{(degrees)}$$

Now where several different component substances of different specific heats and different weights are "mixed" to form one "substance," it follows that:

(41) $$Q = W_1C_1T_1 + W_2C_2T_2 + W_3C_3T_3 + \textit{etc.} \qquad \text{(heat)}$$

Furthermore, it also follows that for the same several different substances:

(42) $$WC = W_1C_1 + W_2C_2 + W_3C_3 + \textit{etc.} \qquad \text{(thermal capacity)}$$

Hence, substituting Fors. (41) and (42) for their equivalents in For. (40), there results:

(43) $$T = \frac{W_1C_1T_1 + W_2C_2T_2 + W_3C_3T_3 + \textit{etc.}}{W_1C_1 + W_2C_2 + W_3C_3 + \textit{etc.}} \qquad \text{(degrees)}$$

which is the same as For. (38).

Example.—If 40 lb. of water at a temperature of 160° F. is mixed with 21 lb. of water at 52° F., what is the temperature of the mixture? It is assumed that no heat is gained or lost by the vessel in which the mixing occurs. Solution.—The specific heat of water is "1." Now substitute in For. (38): $T = (W_1C_1T_1 + W_2C_2T_2)/(W_1C_1 + W_2C_2) = [(40 \times 1 \times 160) + (21 \times 1 \times 52)] \div [(40 \times 1) + (21 \times 1)] = (6{,}400 + 1{,}092) \div (40 + 21) = 7{,}492 \div 61 = 122.82°\ F.$

Example.—A block of wrought iron which weighs 3.25 lb. is heated to a temperature of 780° F. This hot iron block is dropped into a copper pan, which weighs 2 lb. and which contains 7.8 lb. of water. Both the water and the pan are at a temperature of 80° F. What, assuming no

loss or gain of heat to or from outside sources, will be the final temperature of the "mixture"? Solution.—Assume the following specific heats: Copper = 0.095. Water = 1. Wrought iron = 0.114. Now substitute in For. (38): $T = (W_1C_1T_1 + W_2C_2T_2 + W_3C_3T_3)/(W_1C_1 + W_2C_2 + W_3C_3) = [(3.25 \times 0.114 \times 780) + (2 \times 0.095 \times 80) + (7.8 \times 1 \times 80)] \div [(3.25 \times 0.114) + (2 \times 0.095) + (7.8 \times 1)] = 111.0° F.$

Example Illustrating How The Temperature Of A Furnace May Be Determined By Applying The "Method Of Mixtures."—A block of wrought iron which weighs 1 lb. is placed in a furnace and permitted to remain there until it attains the temperature of the furnace. It is then removed and placed in a copper bucket which contains exactly 2 lb. of water at a temperature of 75° F. The copper bucket weighs ½ lb. The final temperature of the mixture is 156° F. What was the temperature of the furnace? (Assume that none of the water is vaporized into steam and that there is no exterior loss or gain of heat by the bucket.) Solution.—Use the values for specific heats which are given in the preceding example. Now transposing For. (38) for T_1 there results $T_1 = [T(W_1C_1 + W_2C_2 + W_3C_3) - (W_2C_2T_2 + W_3C_3T_3)]/W_1C_1$. Now, substituting the values above given in this formula: $T_1 = [156 \times (1 \times 0.114 + 0.5 \times 0.095 + 2 \times 1) - (0.5 \times 0.095 \times 75 + 2 \times 1 \times 75)] \div (1 \times 0.114) = [156 \times (0.114 + 0.048 + 2) - (3.562 + 150)] \div 0.114 = [156 \times 2.162 - 153.562] \div 0.114 = [337.272 - 153.562] \div 0.114 = 183.71 \div 0.114 = 1{,}613° F.$, which is the temperature of the iron block when it was dropped into the water, and therefore the temperature of the furnace.

96. Heat Energy, When Added To A Substance, May Be Expended In Three Ways and in only three ways. (The three different kinds of heat were already mentioned in Sec. 54, in connection with the three possible effects of heat transfer.) The heat energy may be expended in doing: (1) *Vibration work.* (2) *Disgregation work.* (3) *External work. All* of the heat transferred must be expended in one, two, or all three of these ways. Likewise, heat energy when abstracted from a substance may be the result of vibration work, disgregation work, or external work—any one, two, or all three. Thus, as will be shown, the vibration work, disgregation work, and external work may be "positive" or "negative," depending on whether heat energy is added or abstracted and upon the pressure conditions during the transfer of heat. In general, the work will be positive when heat energy is added and will be negative when heat energy is abstracted. These three kinds of work are further explained in following sections.

Example.—(*a*) *Imagine that a piece of ice,* the temperature of which is −60° F. (60° F. below zero) is warmed by the gradual addition of heat. The ice is assumed to be heated in a vessel which is open to the atmosphere. Its temperature will rise gradually up to 32° F. During this warming, the volume of the ice is increased but slightly. Hence, little *external work* was done by the expansion of the ice against the external atmospheric pressure; also, very little work (*disgregation work*) was done in separating the molecules which composed the ice. Therefore, nearly all of the added heat is expended as *vibration work* to increase the temperature of the ice.

(*b*) *When the temperature of the ice reaches* 32° *F.* (due to the gradual heating), a change may be noted. The temperature of the ice ceases to rise as more heat is imparted to it. It is found, however, that the ice gradually changes from the solid to the liquid state—it melts into water; the added heat is expended in *disgregation work.* During the entire melting process, the temperature of the mixture of ice and water remains at the temperature of 32° F.; no *vibration work* has been done. During this change of state, the volume of the substance has been changed; hence, *external work* has also been done. How the addition of heat changes the "state" is explained in Sec. 98.

(*c*) *After all the ice has been melted,* the further addition of heat will again increase the temperature of the substance (now water), which requires *vibration work.* The temperature will increase until it reaches 212° F. During this interval the volume will again increase but little; little *disgregation work* and little *external work* is done. Hence, nearly all of the heat imparted to the water may be said to be expended in *vibration work* in increasing the temperature of the water as in (*a*).

(*d*) *When the temperature of the water reaches* 212° *F.* (due to the continued gradual heating) another change is noted. The temperature of the water ceases to rise as more heat is imparted to it. It is found, however, that the water gradually changes from the liquid to the gaseous state—it evaporates into steam. If the enclosing vessel is large enough, the steam will be collected above the water surface and its volume will be found to rapidly increase forcing out the air which previously occupied this space. Finally, all of the water will be evaporated into steam whose temperature is 212° F. The volume of the steam will be about 1,600 times that of the water just before evaporation began. Hence, during the change from water at 212° F. to steam at 212° F., the heat which was added did two things: (1) It, by the expenditure of *disgregation work,* changed the water into steam. (2) It, by doing *external work,* drove out the air from the enclosing vessel. Hence, the heat was effective in changing the state of the substance and in doing external work but it did not change the temperature of the substance. [Compare with (*b*).]

(*e*) *After the water has all been evaporated into steam,* a further gradual addition of heat will again do *vibration work* and thereby increase the temperature of the substance (now steam). The volume of the steam will at the same time increase quite rapidly and by doing *external work*

force out more air from the containing vessel. The molecules of steam are separated somewhat so that, in a sense, there is a change of state—an expenditure of *disgregation work*—but this change is not as pronounced as those in (*b*) and (*d*) above. Hence, the addition of heat to the evaporated steam is effective in (1) *Doing vibration work* in increasing its temperature. (2) *Doing disgregation work* in changing its state. (3) *Doing external work.*

(*f*) *After the steam is heated to some very-high temperature,* it will again be found that further gradual addition of heat will not increase its temperature. There is still another change of "state." Now the atoms of which the steam molecules are composed (hydrogen and oxygen atoms) will be separated. In other words, the steam will, by the expenditure of *disgregation work,* be *dissociated* into hydrogen and oxygen. Hence, the change may be called a chemical change. The temperature at which this dissociation takes place is, however, so high that it is uncommon in heat engineering. Furthermore, the study of dissociation is beyond the scope of this book and will not be further treated herein. It is mentioned here simply to show that there is change of state which even some gaseous substances may undergo when heated.

97. Vibration Work, symbol W_V, is the work (which can be measured in foot-pounds but is most conveniently measured in B.t.u.) which is done by the vibration heat (Sec. 54). It is the work which is done by added vibration heat on the molecules of a substance in increasing their kinetic energy—vibrational velocity—and, thus in increasing the temperature of the substance. Or similarly it is the work which is done by subtracted vibration heat, in decreasing temperature. Thus, when the temperature of a substance is decreased, the molecules of the substance give up a portion of their kinetic energy —hence, "negative" vibration work is done. *Vibration heat* is, therefore, also called *temperature heat, thermometer heat,* and *sensible heat* (because it is the heat which affects the sense of touch). A formula for vibration work may be written thus:

$$W_V = 778\mathbf{Q}_V \qquad \text{(foot-pounds)} \tag{44}$$

Wherein: W_V = the vibration work, in foot-pounds $\mathbf{Q}_V$ = the vibration heat, in B.t.u. 778 = the mechanical equivalent of heat (Sec. 82). W_V and $\mathbf{Q}_V$ are both positive when the temperature of a substance is raised and are both negative when the temperature is decreased.

Example.—A gas is confined in a closed vessel (Fig. 98) which is protected (insulated) so that no heat can pass through the walls of the vessel.

A wire is led into the vessel and an electric current is passed through the wire. A transformation of electric energy into heat energy takes place and 50 B.t.u. are given to the gas. If the vessel does not permit the gas to expand, how much vibration work is done? Solution.—Since the gas cannot expand, the heat energy cannot do disgregation work nor external work. Hence, the entire 50 B.t.u. is expended as vibration work. By For. (44): *the vibration work* $= W_V = 778Q_V = 778 \times 50 =$ 38,900 *ft.-lb.*

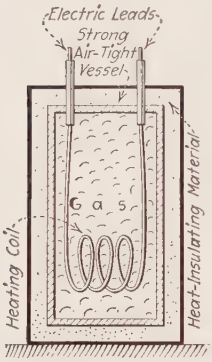


Fig. 98.—A gas being heated in a closed vessel where it cannot expand. Only vibration work is done.

Example.—As a piece of iron is permitted to cool from 600° F. to 80° F., it is found that 250 B.t.u. are given up by the iron. How much vibration work is done? Solution.—Since the temperature has been reduced, Q_V and W_V are both negative. Hence, $Q_V = -250$ B.t.u. and, by For. (44): $W_V = 778\,Q_V = 778 \times (-250) = -194{,}500$ *ft.-lb.*

Note.—Vibration Work Or Vibration Heat Can Be Directly Measured only when the substance which is heated or cooled is so confined that it cannot expand or contract, as in the preceding example. With most solids and liquids, however, the expansion or contraction due to heating or cooling is, in any case, so small that only a negligible error results by assuming that all heat added or abstracted is effective as vibration heat. Hence, for solids and liquids when no change of state occurs, it is practically true that *heat added = vibration heat.* For methods of accurately determining vibration heat, see Sec. 102.

98. Disgregation Work, symbol W_D, is the work which is done by the disgregation heat (Sec. 54). It is the work which is done by added heat on the molecules of a substance in overcoming their mutual attractive forces—in increasing their potential energy by separating them—and, thus, in changing the state (Sec. 49) of the substance; this is called "positive" disgregation work. When heat is given up by a substance during a change of state, this heat is always the result of the work done by the molecules of the substance in drawing each other closer together—in doing "negative" disgregation work. A formula for disgregation work follows:

(45) $$W_D = 778Q_D \qquad \text{(foot-pounds)}$$

Wherein: W_D = the disgregation work, in foot-pounds. Q_D = the disgregation heat, in B.t.u. 778 = the mechanical

equivalent of heat (Sec. 82). W_D and Q_D are both positive when the state is changed from solid to liquid or liquid to gaseous. They are both negative when the state is changed from liquid to solid or gaseous to liquid.

Example.—Assume that there was a liquid which did not expand nor contract in freezing. (Actually, all liquids do either one or the other.) Imagine further that it takes 100 B.t.u. to melt 1 lb. of this substance from the solid to the liquid state (Fig. 99). How much disgregation work is done in melting 1 lb. of this substance? Solution.—Since the temperature of a substance does not change during the melting, no vibration work is done. Also, since the substance does not expand or contract, no external work is done. Hence, the entire 100 B.t.u. is effective in doing disgregation work. By For. (45): the *disgregation work* $= W_D = 778Q_D = 778 \times 100 = 77{,}800$ *ft.-lb.*

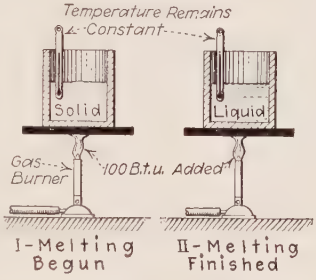


Fig. 99.—Melting 1 lb. of a substance.

Example.—How much disgregation work is done in freezing 1 lb. of the substance of the preceding example? Solution.—During freezing, Q_D and W_D are both negative. Hence, $Q_D = -100$ B.t.u., and by For. (45): $W_D = 778Q_D = 778 \times (-100) = -77{,}800$ *ft.-lb.*

Note.—The Disgregation Work Or Disgregation Heat Can Be Measured Directly only if the heated substance does not expand or contract during a change of state. In practically all cases, the disgregation work or disgregation heat is not measured directly but is computed, as will be explained, from other heat measurements.

99. External Work, symbol W_E, is the work (usually measured most conveniently in foot-pounds) which is done by the external-work heat (Sec. 54). It is the work done by the substance in expanding (Fig. 86) against restricting forces; if a body is heated in the atmosphere then the restricting forces are those which are imposed on the body by the atmospheric pressure—the body must *push away* the atmosphere. It thus does "positive" external work. If, however, during a heat transfer the volume of the body is decreased, then the external forces help to heat the body and "negative" external work is done. A formula for external work follows:

(46) $$W_E = 778Q_E \qquad \text{(foot-pounds)}$$

Wherein: W_E = the external work done, in foot-pounds.

$\mathbf{Q}_E$ = the external-work heat, in B.t.u. 778 = the mechanical equivalent of heat (Sec. 82). W_E and $\mathbf{Q}_E$ are both positive when the volume of the substance is increased; they are both negative when the volume is decreased.

Example.—Assume that a cylinder (Fig. 100) contains 1 cu. ft. of gas at a certain temperature and pressure and that the cylinder is fitted with a piston. Assume, further, that heat is supplied to the gas and the piston is permitted to move out of the cylinder at such a rate that the temperature of the gas does not change. It may here be assumed (it is proved in Sec. 258) that for a gas the disgregation work is zero. If 10 B.t.u. are imparted to the gas, how much external work does the gas do in pushing out the piston? Solution.—Since the temperature remains constant, no vibration work is done and since, as stated in the example, no disgregation work is done, all of the imparted heat must be external work heat. Hence, by For. (46): *the external work* $= W_E = 778\mathbf{Q}_E = 778 \times 10 = 7{,}780$ *ft.-lb.*

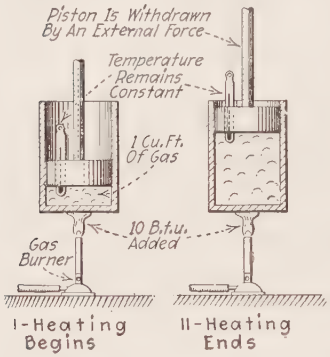


Fig. 100.—Heating a gas and maintaining a constant temperature.

Note.—External Work Is (As Further Explained In Following Sec. 263) Usually Determined From The Pressure-volume Relations During The Addition Of Heat.—If the body is subjected to a constant pressure during the heating, then (see Sec. 263 for the derivation of this formula):

(47) *External work = pressure × change in volume*

Or, expressing the same thing with symbols:

(48) $$W_E = P \times (V_2 - V_1) \qquad \text{(ft.-lb.)}$$

Wherein: W_E = the external work, in foot-pounds. P = pressure, in pounds per *square foot*. V_2 and V_1 = the final and initial volumes, respectively, of the body, in cubic feet.

If, during the heating, the pressure is not constant, then

(49) *External work = average pressure × change in volume* (ft.-lb.)

Or, the external work may be found directly from a pressure-volume diagram as explained in Sec. 262.

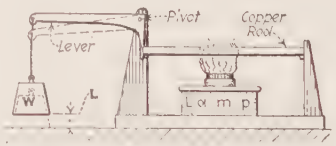


Fig. 101.—An expanding rod may do work.

Example.—The weight W (Fig. 101) weighs 10 lb. The distance, L, through which the weight has been lifted by the expansion of the copper

rod, is 0.02 in. Therefore, *the work done—the energy expended—by the external heat which has manifested itself in expanding the rod* = $10 \times 0.02 = 0.2$ *in.-lb.*

100. If The Quantity Of Heat Which Is Transformed Into Mechanical Energy By The Expansion Of A Solid Or Liquid Were Restrained From Such Transformation, the heat would then expend its energy solely in raising the temperature. Thus it would manifest itself solely as vibration or sensible heat—instead of as external-work heat as in Fig. 101.

EXPLANATION.—Imagine an iron rod (Fig. 102) to be encased in a massive steel die, and to be heated by an electric current. The rod would tend to expand. But expansion would be prevented, in all directions, by the steel die. Hence, no external (mechanical) work could or would be done. No external-work heat could be expended. But the heat which would be transformed into mechanical work, if the rod were free to expand, would, nevertheless, manifest itself as vibration work in raising the temperature of the constrained rod. Hence, the temperature of this embedded rod would be higher than it would be if the rod were free to expand.

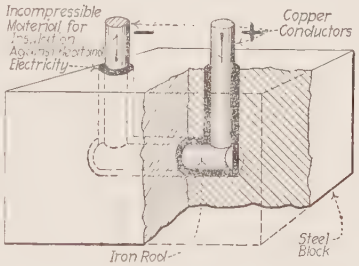


FIG. 102.—Imaginary construction of steel dies for preventing expansion of iron rod.

101. The Fundamental Heat Transfer Equation is merely a formula expressing the facts of Sec. 54. It may be written:

$$Q = Q_V + Q_D + Q_E \qquad \text{(British thermal units)} \tag{50}$$

Wherein: Q = the total heat transfer, in British thermal units. Q_V = change in vibration heat, in British thermal units. Q_D = change in disgregation heat, in British thermal units. Q_E = external-work heat, in British thermal units.

If the heat effects are to be expressed in foot-pounds it follows that, since 1 *B.t.u.* = 778 *ft.-lb.* (Sec. 82), the formula will become:

$$Q = \frac{1}{778}(W_V + W_D + W_E) \qquad \text{(British thermal units)} \tag{51}$$

EXAMPLE.—A certain weight of a certain liquid substance is changed, by heating, into a vapor, at an increased temperature. To effect the change it is found that: 140 B.t.u. is expended in the external work

which is done by the substance, during the process, due to the increased volume of the substance; 360 B.t.u. is expended in raising the temperature of the substance; 1,800 B.t.u. is expended in changing the state of the substance from a liquid to a gas. What total amount of heat must be transferred to the substance to effect the change? SOLUTION.—Substituting in For. (50): $Q = Q_V + Q_D + Q_E = 360 + 1{,}800 + 140 = 2{,}300$ *B.t.u.* = *Total heat transferred.*

EXAMPLE.—It is found, by experiment, to require 1,150.4 B.t.u. to raise the temperature of 1 lb. of water from 32° F. to 212° F. and evaporate it into steam when all of the heating is done in an open vessel (atmospheric pressure). The final volume of the evaporated steam is 26.79 cu. ft. The initial volume of the water at 32° F. was approximately 0.016 cu. ft. What is the vibration heat, disgregation heat, and external-work heat? SOLUTION.—By definition of the British thermal unit, 180 B.t.u. are required to raise the temperature from 32° F. to 212° F. By the example under Sec. 96, this may be taken as *vibration heat.* By For. (48): $W_E = P \times (V_2 - V_1) = (14.7 \times 144) \times (26.79 - 0.016) = 56{,}650$ *ft.-lb.* Now, by For. (46), transposed: *the external-work heat* $= Q_E = W_E/778 = 56{,}650 \div 778 = 72.8$ *B.t.u.* Also, by transposing For. (50): $Q_D = Q - (Q_V + Q_E) = 1{,}150.5 - (180 + 72.8) = 897.6$ *B.t.u.* = *disgregation heat.*

102. How The Heat Energy Does Work When A Solid Body Is Heated.—A solid body expands but little; the disgregation and external works are therefore small. When the vibration work is being considered, the disgregation work and the external work may ordinarily be neglected. When a solid body is heated, as for example a piece of iron, it is therefore, generally assumed that all of the heat is used in raising the temperature. Or, when a solid is heated:

(52) $Q = Q_V$ (very nearly) (British thermal units)

103. How The Heat Energy Does Work When A Solid Is Melted To The Liquid State.—During the melting of a solid body there is no change in its temperature; hence, no vibration work is done during the melting. Furthermore, when a body melts there is usually only a very small change in volume although some bodies expand and others contract as they melt. Hence, very little external work is usually done by the body in melting. Nearly all of the added heat is used in doing disgregation work—in overcoming the mutual attractive forces between the molecules and giving them the freedom which they have in the liquid state. Therefore, if the small

amount of external work is neglected, all of the added heat (the latent heat of melting, Sec. 106) is effective in doing disgregation work; or, expressed as a formula:

(53) $Q = Q_D$ (very nearly) (British thermal units)

Note.—When A Liquid Is Heated, the conditions are almost the same as when a solid is heated—expansion is very small, usually, and the disgregation and external works may ordinarily be neglected when the vibration work is being considered. Hence, For. (52) applies equally well to the heating of solids and liquids.

104. How The Heat Energy Does Work When A Liquid Is Vaporized.—As there is no change in temperature while a liquid is being vaporized, no vibration work is done. Now during vaporization the volume of the substance is increased many fold; therefore a considerable quantity of external work is done. However, by far the greater fraction of the latent heat of vaporization is used in doing disgregation work—in separating the molecules against their mutual attractive forces. During vaporization, therefore,

(54) $Q = Q_D + Q_E$ (British thermal units)

105. How The Heat Energy Does Work When A Gas Is Heated.—In a gas the molecules are so far apart in comparison to their own size that the attraction of one for the other is so small that it is inappreciable. Hence, practically no work is necessary to separate them farther. Therefore the disgregation work is zero and the formula becomes:

(55) $Q = Q_V + Q_E$ (British thermal units)

Note.—The Relative Magnitudes Of The Vibration And External-work Heats Depends On the conditions under which the gas is heated, this is further explained in Div. 8. Suppose that the air in a cylinder is being heated (Fig. 100). The piston may be held in one position during the heating; then no external work will be done and Q_E will be zero (because the air cannot expand and do external work) and all of the heat must then go toward raising the temperature. Or, the piston may be raised by an external force at such a rate that the temperature will decrease, due to expansion, just as fast as it tends to rise due to the heating; under such conditions the temperature will remain constant ($Q_V = 0$) and all of the heat will be expended in doing external work.

106. Latent Heat is the heat energy which is required to produce changes in the physical state (Sec. 49) of a substance—to change it from solid to liquid, from liquid to gas, or the

reverse of either. Thus, the change of physical state may be either a melting, freezing, vaporization (evaporation), or condensation. During melting and vaporization, heat must be supplied to the substance; during freezing and condensation heat must be abstracted from it. Furthermore, the amount of heat which must be supplied during the melting of a given weight of a substance is the same as that which must be abstracted while it freezes under the same conditions. The amount of latent heat required for melting or freezing is called the *latent heat of melting* or the *latent heat of fusion.* Likewise, during the vaporization of a certain weight of a substance the same amount of heat must be supplied as must be abstracted from it in condensing it. The amount of heat which must be transferred to or from a substance during its vaporization or condensation is called the *latent heat of vaporization* or the *latent heat of evaporation.*

Note.—The Latent Heat Is The Sum Of The Disgregation And External-work Heats.—This follows from the fact that, during a change of state (under constant pressure), the temperature of a substance does not change. Hence, no vibration heat is necessary to effect the change and

(56) $$Q_L = Q_D + Q_E$$ (British thermal units)

Wherein: Q_L = the latent heat of the substance, in British thermal units. Q_D = the disgregation heat during a constant-pressure change of state, in British thermal units. Q_E = the external-work heat during the constant-pressure change of state, in British thermal units.

Explanation.—Suppose a solid substance, as an ingot of lead, is heated until its temperature rises exactly to the melting point. The heat absorbed by the substance up to this point increases the motion of the molecules and is called (Sec. 54) vibration or sensible heat.

Now, if more heat be added to the ingot, it will instantly begin to melt. But its temperature will not rise. The heat energy which is now absorbed by the ingot is expended entirely in the work of melting—in transforming the molecular structure from the solid to the liquid state. It is disgregation heat. None of the heat is available for raising the temperature while the work of melting is going on—it is all used in separating the molecules. Hence the temperature will continue constant until the ingot is wholly melted. But at the exact instant when the melting is complete, the temperature of the molten lead will, if the heating still continues, begin to rise. The heat which was absorbed by the lead while its temperature remained stationary is its latent heat of melting. The latent heat of melting is further explained in Sec. 289 and the latent heat of vaporization in Sec. 322.

EXAMPLE.—What is the latent heat of vaporization of 1 lb. of water at atmospheric pressure? SOLUTION.—By the example under Sec. 101, Q_D = 897.6 B.t.u. and Q_E = 72.8 B.t.u. Hence, by For. (56): *the latent heat* = $Q_L = Q_D + Q_E = 897.6 + 72.8 = 970.4$ *B.t.u.*

NOTE.—LATENT HEAT MAY EXIST WITHIN A HEATED SUBSTANCE, EVEN WHEN THERE IS NO OUTWARD MANIFESTATION OF A PHYSICAL CHANGE in the substance. The latent heat present in such cases will not, however, manifest itself until a change in state occurs. Thus, water at ordinary atmospheric temperatures contains its latent heat of melting but this latent heat does not manifest itself (show its presence) until the water is cooled to the freezing point and begins to solidify or freeze.

107. "Internal Heat" Or "Intrinsic Heat" is the heat energy which is expended in doing work on the molecules both in increasing their vibrational velocity—kinetic heat energy—and in separating them against their forces of mutual attraction—increasing their potential heat energy (Sec. 52). It is the heat inside the substance. It does not include the heat energy which is expended in separating the molecules against external forces—in doing external work. Hence, during any heat transfer to or from a substance, the change in internal heat:

(57) $Q_I = Q_V + Q_D$ (British thermal units)

(58) $Q = Q_I + Q_E$ (British thermal units)

Wherein: Q_I = the change in internal heat, in British thermal units. Q_V = the change in vibration heat, in British thermal units. Q_D = the change in disgregation heat, in British thermal units. Q = the total heat transfer, in British thermal units. Q_E = the change in external-work heat, in British thermal units.

EXAMPLE.—How much internal heat is expended in changing 1 lb. of water from the liquid state at 32° F. to the steam state at 212° F.? SOLUTION.—By the example under Sec. 101, Q_V = 180 B.t.u. and Q_D = 897.6 B.t.u. Hence, by For. (57): the change in *internal heat* = $Q_I = Q_V + Q_D = 180 + 897.6 = 1{,}077.6$ *B.t.u.*

108. The Total Heat Of A Substance, or as it is often termed, the *total associated heat*, is, strictly speaking, the total heat energy, in the substance above the absolute zero of temperature. Actually, in practice, "total heat" is, unless otherwise specified, taken to mean the *total heat in the substance above some arbitrarily-chosen convenient reference temperature.*

NOTE.—With present means for making heat determinations it is impossible to definitely compute the total-heat contents of substances

from absolute zero. Hence, it is necessary to regard some convenient degree of temperature and state as the "zero," datum point or basis for heat computations. In dealing with water and steam, the heat energy of water (in liquid form) at 32° F. is generally taken as the arbitrary zero of heat energy (see also Sec. 365). This procedure works no hardship since we are usually, in practice, interested in the amount of heat which is transferred to or from a substance, rather than in the total amount of heat which it contains above absolute zero.

Example.—What is the total heat of 1 lb. of water at 100° F? at 212° F.? Of 1 lb. of steam at 212° F.? Solution.—By Fcr. (32), for water heated from 32° F. (the datum point) to 100° F., the *total heat* = $Q = CW(T_2 - T_1) = 1 \times 1 \times (100 - 32) = 68$ *B.t.u.* Likewise, for water at 212° F., the *total heat* = $1 \times 1 \times (212 - 32) = 180$ *B.t.u.* As given in the example under Sec. 101, for steam at 212° F., the *total heat* = 1,150.4 *B.t.u.*

QUESTIONS ON DIVISION 4

1. What properties of a substance determine the amount of heat energy that the substance contains?

2. What was the ancient philosophers' theory of the nature of heat?

3. What is the unit that is used in English-speaking countries for measuring quantities of heat? Give its definition.

4. Give the formula for computing the quantity of heat necessary for raising the temperature of water by a specified amount.

5. What is a small calorie? A large calorie? How are they related in size to the British thermal unit?

6. State the first law of thermodynamics. Is a British thermal unit the equivalent of any certain number of foot-pounds? If so, what is the number and what is it called?

7. Draw a sketch of the apparatus and explain how the mechanical equivalent of the British thermal unit is determined. Do the same for an electrical method.

8. State the second law of thermodynamics. What is the most important consequence of this law?

9. Can you give a hydraulic interpretation of the second law?

10. Can the conversion of heat energy into mechanical energy ever be complete? Explain fully and give a hydraulic analogy.

11. Is the conversion of mechanical energy into heat energy ever complete? Give an example and a hydraulic analogy.

12. What is meant by the *thermal capacity* of a substance? Is it always the same for a given substance? Give examples.

13. What is meant by the *specific heat* of a substance? How does it differ from thermal capacity? What is another name for the specific heat?

14. Have all substances the same specific heat? Explain as fully as you can and give some numerical values.

15. How can the specific heat of a substance be determined? Give the formula.

16. How would you determine how much heat must be added to a substance of known specific heat in order to raise its temperature a given amount? Give the formula.

17. Draw a sketch and describe the method of finding the specific heat of a substance by the method of mixtures.

18. In what three ways may heat energy, when added to a substance, be expended? Explain the effects of the heat energy that is added in raising the temperature of ice from below the freezing temperature to a very high temperature.

19. What is meant by *vibration work*? What is the heat called that is effective in doing vibration work? Give an example of vibration work and give the formula. When and how is it measured directly?

20. What is meant by *disgregation work?* The heat which does disgregation work is how termed? Give an example of heat doing disgregation work. Give the formula. How is disgregation work measured?

21. What is meant by *external work?* The heat which does external work is how termed? Give the formula for external work. How is it generally measured? Give an example of heat doing external work.

22. State the fundamental heat-transfer equation. Upon what is it based? Give an example of its application.

23. How does heat energy do work when a solid body is heated? Explain.

24. How does heat energy do work when a solid is melted? Explain.

25. How does heat energy do work when a liquid is heated? Explain.

26. How does heat energy do work when a liquid is vaporized? Explain.

27. How does heat energy do work when a gas is heated? Explain. What are the relative magnitudes of the two kinds of work?

28. What is the meaning of the term *latent heat? Latent heat of melting? Of fusion? Of vaporization?* What two kinds of work are done by the latent heat?

29. What is the meaning of *internal heat?* What is another name for it? What two kinds of work are done by the internal heat?

30. What is meant by the *total heat* of a substance? Why is the total heat not usually used in engineering calculations? What is used instead?

PROBLEMS ON DIVISION 4

1. A bucket containing water is placed over a fire for heating. The temperature of the water is 55° F. Its weight is 35 lb. How much heat must be added to it to raise its temperature to the boiling point which is 212° F.?

2. What would be the temperature of 8 lb. of water which had an original temperature of 60° F., after 265 B.t.u. of heat has been added to it?

3. A boiler in a heating system is known to be 50 per cent efficient. The boiler is refilled with water at a temperature of 65° F. After burning the coal which liberates 50,000 B.t.u., the water has a temperature of 210° F. What is the weight of the water in the boiler?

4. After a certain time, the temperature of 15 liters of water, contained in a closed vessel, is found to be decreased 35° C. How many large calories of heat have been lost? How many B.t.u.? (A liter of water weighs one kilogram.)

5. In a certain power plant, it is found by test that an engine is delivering, as available work, 12 per cent. of the heat in the coal which is burned. If 17 lb. of coal are burned in one hour, what is the amount of energy delivered by the engine per hour? What horsepower is the engine delivering? (Assume that the coal contains 14,000 B.t.u. per lb.)

6. In a specific-heat determination, 8.75 B.t.u. are added to 4.5 lb. of nickel. It is found that the nickel temperature increases from 65 to 83° F. What is the specific heat of the nickel?

7. A soft-steel plate which weighs 75 lb. is heated from 80 to 1500° F. Assuming that the mean specific heat of the steel is 0.115, how many B.t.u. are necessary to effect this increase in temperature?

8. Assuming that the specific heat of cast iron is 0.119, how many foot-pounds of energy are required to heat a 125-lb. iron casting from 40 to 180° F.?

9. In a certain boiler furnace, it is known that for each pound of coal burned, 30 lb. of air are supplied. This air must be heated from 65° F., and passes up the stack at a temperature of 565° F. Assuming that the specific heat of air for this temperature range is 0.24, calculate the B.t.u. necessary to heat the air for each pound of coal which is burned.

10. A 6-lb. iron casting has been heated in a furnace to a temperature of 2,300° F. It is dropped into a bucket which contains 5 gal. of water at 50° F. What will be the temperature of the water in the bucket? (Assume that the specific heat of the iron is 0.119 and that 1 gal. of water weighs 8.3 lb.)

11. If 16 lb. of water at 40° F. is mixed with 10 lb. of water at 110° F., what will be the temperature of the resulting mixture?

12. A 12-lb. iron ball is heated to a temperature of 212° F. It is then dropped into 8 lb. of water at 35° F. The water temperature rises to 60° F. Compute the specific heat of the iron.

13. In Prob. 1, how much vibration work, in foot-pounds, is done?

14. If it takes 10.5 B.t.u. to melt 1 lb. of lead at its melting point of 626° F., how much disgregation work, in foot-pounds, is done on each pound of lead during the melting process?

15. Water, when under a pressure of 100 lb. per sq. in. abs., boils at 327.8° F. and, at that temperature, 1 lb. occupies a volume of 0.0177 cu. ft. When evaporated into steam at the same pressure and temperature, it occupies 4.429 cu. ft. How much external work is done in the vaporization process?

16. If, when water is evaporated under a pressure of 100 lb. per sq. in. abs. (as in Prob 15), 806.6 B.t.u. of disgregation heat are required, what is the latent heat of vaporization?

17. How much vibration heat is required to raise the temperature of 1 lb. of water from 32° F. to 327.8° F. if the specific heat of the water is 1?

18. Using the results of preceding problems, compute how much more internal energy there is in 1 lb. of steam at 100 lb. per sq. in. abs. than in 1 lb. of water at 32° F.

19. Using the results of preceding problems, compute the total heat of 1 lb. of steam at 100 lb. per sq. in. abs.

DIVISION 5

TRANSFER OF HEAT

109. Heat May Be Transferred.—If one end of a copper wire is heated, some of the heat will travel through the wire. Shortly the other end will be hot. Heated air, from the furnace in the basement of a dwelling, flows (Sec. 137) through ducts and registers into the rooms above and produces an agreeable warmth on wintry days. In cold weather the house cat curls up in front of the open fireplace in order to feel the heat which emanates from the fire.

110. Heat Is Transferred In Three Different Ways.—(1) *By conduction.* (2) *By convection.* (3) *By radiation.* Heat transfer from one body to another may occur simultaneously by one, two, or all three of these methods.

111. Heat Conduction Is Transfer Of Heat Through The Molecules Of A Substance.—Heat has been shown (Sec. 52) to be a vibratory motion of the molecules. When heat is added to any part of a body, as to one end of a copper bar, the molecules in that part vibrate more rapidly. This causes them to strike violently against the molecules in the cooler part immediately adjacent. The rapidity of the vibration among the molecules in this part is thereby also increased, and the part becomes heated. These molecules, in turn, strike violently against the molecules in the cooler part next farther away from where the heat is added initially. Thus, by successively transmitting the increased speed of vibration, the molecules conduct the heat to remote parts of the body, as to the opposite end of the copper bar.

Note.—Conduction Of Heat Occurs More Or Less In All Substances.—In no case, however, will conduction cause that part of a body (*A*, Fig. 103) which is farthest from the source of heat, *H*, to acquire as high a temperature as the part, *B*, which receives the heat directly. In fact (Sec. 55) there must be a temperature difference—or thermal pressure—between one point and another point, to which heat is conducted, to effect the conduction.

112. There Are Two Modes Or Forms Of Conduction.—(1) *Internal conduction,* whereby heat is transmitted from molecule to molecule within a body. (2) *External conduction,* whereby heat is transmitted from the molecules of one body to the molecules of another body, when the two bodies are in contact.

Examples.—When the entwined ends of the metal rods (*B*, Fig. 103) are heated by the flame, *H*, the free ends *A* and *A* of the rods, due to

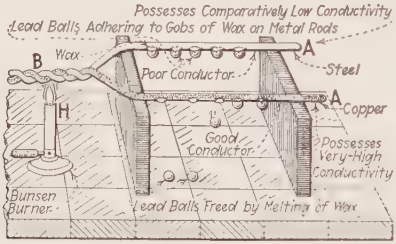


Fig. 103.—The copper wire, which is a good conductor, transmits the heat more rapidly than does the steel wire.

internal conduction, likewise become heated. As the metal rods (Fig. 103) become heated, some of the heat is absorbed, due to external conduction, by the bits of wax which bond the lead balls to the rods. This causes the wax to melt, thus releasing the lead balls.

The iron boiler tube (Fig. 104) absorbs heat from the hot gases. The heat flows, due to internal conduction, from the outer to the inner

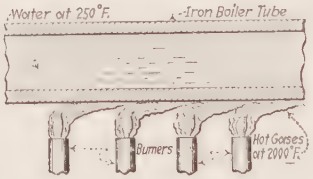


Fig. 104.—Heat conducted through the boiler tube from the hot gases to the water.

surface of the tube. It passes thence, due to external conduction, to the water which is in contact with the tube.

113. The Factors Which Determine The Total Transfer Of Heat By Conduction through a substance are these: (1) *The nature of the substance.* (2) *Its cross-sectional area.* (3) *The thermal pressure or temperature difference.* (4) *The length of time during which the flow occurs.* (5) *The length of the heat*

path through the substance. Each of these factors is discussed further in succeeding sections.

114. The Nature Of A Substance Affects Its Ability To Conduct Heat.—That is, the molecules of some substances transmit the heat-energy motion, from one to another, more effectively than do the molecules of certain other substances.

Examples.—Metals are good heat conductors. Liquids (Fig. 105) are poor conductors. Air (Figs. 106 and 107) and other gases are very poor conductors. A perfect vacuum would not conduct at all because there would be no molecules in it to transmit the heat-energy motion. Some solids, such as wood and cork are poor conductors. Wooden

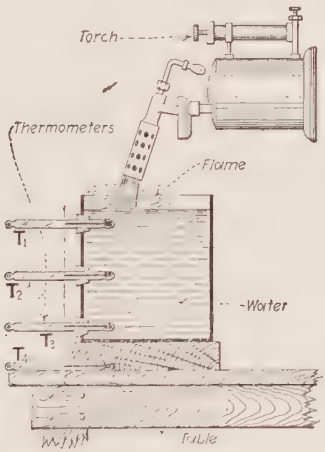


Fig. 105.

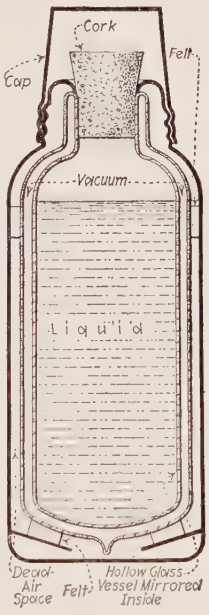


Fig. 106.

Fig. 105.—Showing that water is a poor conductor of heat. (Although the water film at the surface is boiling, all four thermometers T_1, T_2, T_3 and T_4 read practically the same temperature.)

Fig. 106.—Sectional elevation of typical "thermos" flask.

heat insulators (Fig. 108) are sometimes interposed in metallic tea-pot handles to prevent the hand-hold from becoming unduly heated. Cork linings and dead-air spaces are arranged in cold-storage-room walls (see Sec. 619) to minimize the loss of heat through them.

Note.—Air Is An Important Heat Insulating Material.—Any material or structure, which is composed largely of pockets of non-circulating air, provides good heat insulation. Hence, feathers, fur, felt, cork, magnesia and cellular asbestos are all good heat insulators. Like-

wise a blanket of freshly fallen snow protects both the vegetation and the ground upon which it falls from freezing.

Note.—The Fireless Cooker (Fig. 109) provides a good example of the utilization of the poor heat-conducting properties of certain materials.

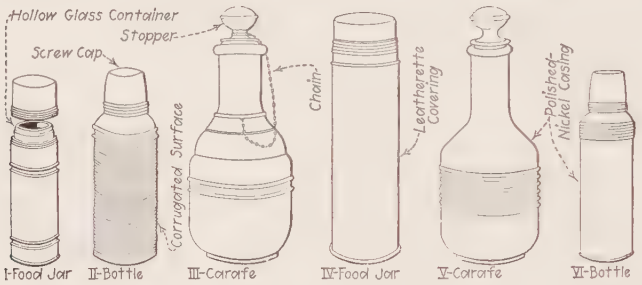


Fig. 107.—Some thermos bottles and containers. (See preceding illustration. The dead air space is a very poor heat conductor. The vacuum chamber is almost opaque to heat flow. The mirrored surfaces minimize heat radiation.)

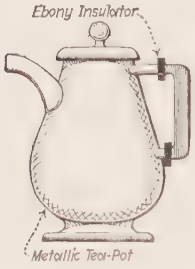


Fig. 108.

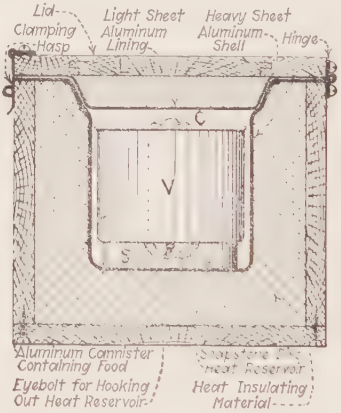


Fig. 109.

Fig. 108.—Heat "insulators" in metallic tea-pot handle.

Fig. 109.—A fireless cooker—food in cannister V, is heated on a stove to cooking temperature. Disc, S, is likewise heated to a relatively high temperature. S and V are then inserted in cooker. Lid L is closed and clamped. Insulation minimizes loss of heat. Heat retained in cooking shell, C, is absorbed by the food. Thus the food is cooked to completion without further attention or heating.

115. The Amount Of Heat Which Will Be Transmitted Through Substances By Conduction Varies Directly As Their Cross-sectional Areas, other conditions being the same. The area is always taken at right angles to the direction of heat flow.

EXAMPLE.—A certain copper rod having a cross-sectional area of 2 sq. in. conducts 13 B.t.u. of heat in a minute. Then, other conditions remaining unchanged, a similar copper rod but of 4 sq. in. sectional area would conduct: $2 \times 13 = 26$ *B.t.u. in a minute*—twice the sectional area, hence twice the conduction.

116. Heat-flow By Conduction Between Two Points In A Substance Varies Directly As The Thermal Pressure, Which Is The Temperature Difference, Between Them, other conditions being the same. Just as there must be a difference of

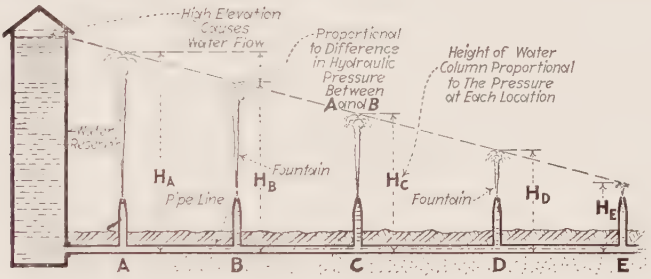


FIG. 110.—Difference of pressure causes water to flow through pipe line. (Drop of pressure from *A* to *E* is indicated by decreasing heights of fountains. The drop of pressure is caused by friction.)

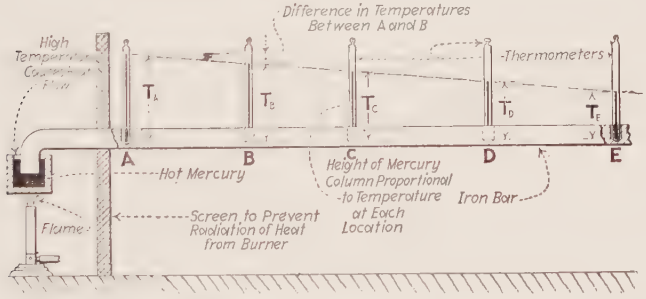


FIG. 111.—Difference in temperature causes heat to flow through iron bar. (Drop of temperature from *A* to *E* is indicated by decreasing heights of thermometer mercury columns. The drop in temperature is due to thermal resistance. In the above diagram it is assumed that no heat is lost from *AE* by radiation. All is conducted from the flame through and past *E* to a colder body.)

hydraulic pressure (Fig. 110) to cause water to flow in a pipe and a difference of electric pressure (voltage) to force electricity to flow in a wire, so there must be a difference of thermal pressure—or temperature—to cause heat (Fig. 111) to flow in

a substance. The flow is always from a point of higher to one of lower temperature.

Example.—Assume that, in Fig. 111, the temperature at B is 85° F. and that at C is 80° F. Then, the heat flow from A to B would be proportional to: 85 − 80 = 5° F. = *thermal pressure* = *temperature difference*. Suppose that, with this thermal pressure of 5° F., the heat flow from B to C is 50 B.t.u. per min. Now, if the temperature at B were increased to 90° and that at C remained at 80°, the thermal pressure would then be 90 − 80 = 10°. Hence, with the thermal pressure thus doubled, the heat flow would also be doubled and would now be: $2 \times 50 = 100$ *B.t.u. per min.*

117. Heat-flow By Conduction Between Two Points In A Substance Varies Directly As The Length Of Time During Which The Flow Occurs, other conditions being the same. The greater the elapsed time the greater will be the total amount of heat which is transferred.

Example.—If 40,000 B.t.u. flow from the outside to the inside of a cold-storage chamber in 1 hr., then, in 2 hr. twice the heat or, $2 \times 40{,}000 = 80{,}000$ *B.t.u.* will be transferred, it being assumed that temperature and all other conditions are the same in both cases.

118. Heat-flow By Conduction Between Two Points In A Substance Varies Inversely As The Length Or Distance Between The Points, other conditions being the same. The ideal condition, of no loss of heat from the substance by either radiation or convection, is here assumed. The greater the distance the less will be the flow, other conditions being equal.

Example.—If in Fig. 111 with a temperature difference of 10° F. between A and C, the heat flow between A and C is 600 *B.t.u. per min.*, then between A and E, which is twice the distance a 10° difference would force only $600 \div 2 = 300$ *B.t.u. per min.*

119. "Thermal Conductance" is a term used to signify the ease or readiness with which a substance conducts heat. Conductance is, in a sense, the opposite (actually it is the reciprocal) of thermal resistance, which is defined in Sec. 129. The greater the conductance of a substance the more readily will it transfer heat by conduction. All substances do not conduct heat with equal facility.

Examples.—The conductance of some substances, as silver (see Table 125) is very high. That of others, as asbestos, is very low. The former

are called *good heat conductors*. The latter are called *poor heat conductors* or *heat insulators*. The copper rod of Fig. 103 is a good conductor. The steel rod is, by comparison, a poor conductor. Therefore, the heat travels

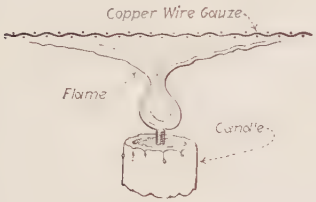


FIG. 112.—Gas burning below a copper-wire-gauze screen. The gauze conducts the heat away from the flame, thus extinguishing the flame before it can pass through the gauze.

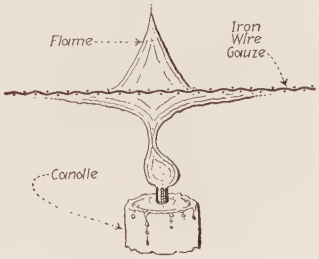


FIG. 113.—Gas burning above iron-wire gauze.

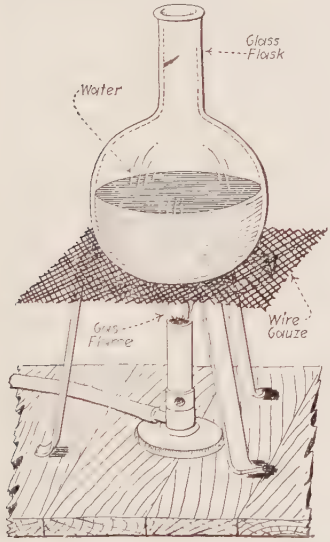


FIG. 114.—Wire gauze prevents the hot flame from touching the glass. It distributes the heat, hence the glass flask does not break.

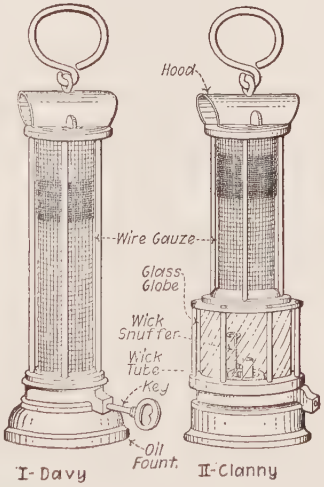


FIG. 115.—Miners' safety lamps of primitive Davy and Clanny types.

more rapidly through the copper than through the steel. This is indicated by the melting of the gobs of wax on the copper rod before the melting of the wax on the steel rod occurs.

EXAMPLE.—The copper-wire-gauze screen of Fig. 112 has high thermal conductance. Therefore the heat, which is absorbed by the central area

which is directly in contact with the flame, passes rapidly outward, through the surrounding area, to the edges of the screen. Hence, the central area does not retain sufficient heat to ignite the gas which penetrates above the screen. An iron-wire-gauze screen (Fig. 113) has, by comparison with the copper screen of Fig. 112, poor conductance. It follows that the heat absorbed by its area which is in contact with the flame is transmitted but slowly through the surrounding area. Hence, the central area retains sufficient heat to quickly ignite the gas which penetrates above the screen.

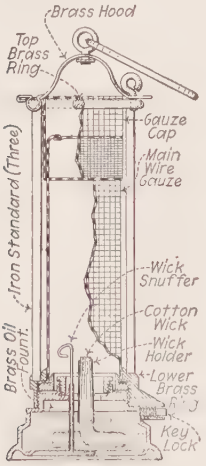


Fig. 116.—Sectional elevation of Davy lamp. (Bureau of Mines Circular No. 12.)

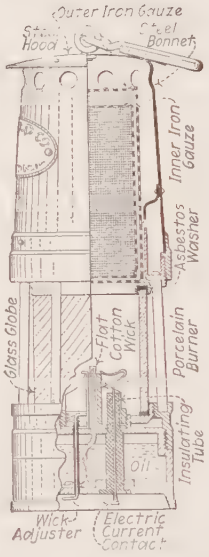


Fig. 117.—Recent bonneted pattern of Clanny-type lamp. (Bureau of Mines Circular No. 12.)

Examples.—Due to its high conductance, the copper screen (Fig. 114) distributes the heat of the gas flame over a comparatively large area beneath the glass flask. Cracking of the glass, by concentration of the heat is, thereby, prevented. Due to the high heat conductance (Fig. 112) of the metal of which they are made, the wire-gauze screens (Figs. 115, 116 and 117) which surround the flames in miners' lamps prevent ignition of explosive gases in mines.

Note.—Thermal Conductance In Heat Flow Is Somewhat Analogous To Electrical Conductance In Electricity Flow.—In fact it is generally true that substances which are good conductors of electricity are also good conductors of heat.

Note.—If The Nature Of A Substance Is Such That The Vibratory Motion Of The Molecules In That Part Of A Substance Which Is At The Higher Temperature, Is Transmitted With Great

RAPIDITY to the molecules in the cooler portions, then the conductance of the substance is high. But if the transmission proceeds sluggishly, then the conductance is low.

120. A Unit Of Thermal Conductance Is The "Moht" (pronounced, mote). *A body has a conductance of* 1 *moht when a thermal pressure—or a temperature difference—of* 1° *F. will force through it by conduction* 1 *B.t.u. per hr.* The moht is somewhat analogous to the "mho," which is the unit of electrical conductance. In following sections it is explained how the conductance, in mohts, of a given volume of a given material may be computed.

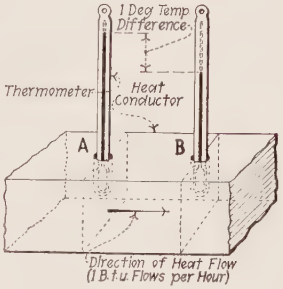


FIG. 118.—Illustrating the "moht."

NOTE.—"MOHT" IS MERELY "THOM" SPELLED BACKWARDS. The "thom" is a unit of thermal resistance as is explained in Sec. 132. Since conductance is the reciprocal—or in a sense the opposite—of resistance, the derivation of the terminology is apparent.

EXAMPLE.—In Fig. 118 the conductance of the material between planes *A* and *B* is just 1 moht because it permits just 1 B.t.u. of heat energy to flow per hour with the thermal pressure of 1° F. This satisfies the definition of the moht.

EXAMPLE.—Fig. 119 shows some values of conductance of a square-foot-inch (1 in. thick and 1 ft. square) of some common substances. Fig. 120 shows similar values for an inch-cube These data are taken directly from Table 125.

121. To Compute The Total Heat-energy Flow Through A Substance By Conduction When Its Conductance, In Mohts, And The Thermal Pressure Are Known, it is merely necessary to substitute in the following formula, the derivation of which will be obvious from a consideration of the preceding definitions:

(59) *Heat flow* = (*Conductance*) × (*Thermal Pressure*)

Or, substituting for the above their equivalents as hereinbefore defined:

(60) *B.t.u. per hour* = $\mathbf{B}(T_2 - T_1)$

Then, if **Q** = total quantity of heat which flows, in B.t.u., it is apparent that:

(61) $\mathbf{Q} = \mathbf{B}t(T_2 - T_1)$ (B.t.u.)

Wherein: t = time, in hours, during which the heat flow takes place. T_2 = temperature on hot end, in degrees Fahrenheit. T_1 = temperature on cold end, in degrees Fahrenheit. **B** = the conductance, in mohts.

Example.—A slab of copper ½ in. thick and 1 ft. square has a conductance of 4,200 mohts. Then if the temperature on one side of the slab is 42° F. and that on the other is 47° F., *the total heat which flows through it in 2½ hr.* = $Q = Bt(T_2 - T_1) = 4{,}200 \times 2.5 \times (47 - 42) = 4{,}200 \times 2.5 \times 5 = 52{,}500$ *B.t.u.*

Note.—By transposing For. (61) there result:

$$B = \frac{Q}{t(T_2 - T_1)} \qquad \text{(mohts)} \tag{62}$$

and

$$(T_2 - T_1) = \frac{Q}{t\,B} \qquad \text{(degrees Fahrenheit)} \tag{63}$$

also

$$t = \frac{Q}{B\,(T_2 - T_1)} \qquad \text{(hours)} \tag{64}$$

Example.—What is the conductance of the bar of Fig. 111 if, when the temperature at A is 800° F. and that at E is 250° F., the total heat which flows from A to E in ¼ hr. is 1,100 B.t.u.? Solution.—Substitute in For. (62): $B = Q/[t\,(T_2 - T_1)] = 1{,}100 \div [0.25\,(800 - 250)] = 1{,}100 \div 0.25 \times 550 = 8$ *mohts.*

Example.—What thermal pressure or temperature difference will, in 1½ hr., force 180,000 B.t.u. through a body which has a conductance of 200 mohts? Solution.—Substitute in For. (63): $(T_2 - T_1) = Q/t\,B = 180{,}000 \div (1.5 \times 200) = 180{,}000 \div 300 = 600°\,F.$ = *thermal pressure = temperature difference.*

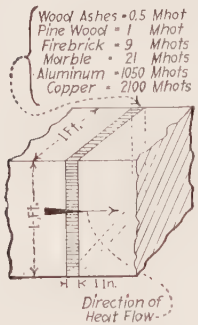


Fig. 119.—Showing conductance of some common materials, in mohts per square-foot-inch.

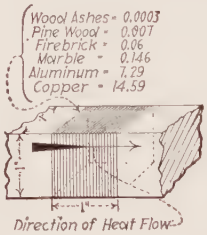


Fig. 120.—Showing conductances, in mohts per inch-cube.

122. Thermal Conductivity Is Specific Thermal Conductance.—That is, it is the conductance of a unit block of the

material under consideration, which has a specified length and cross-sectional area. Frequently, in heat computations, the conductance of a slab of the material (Fig. 119) which has a sectional area of 1 sq. ft. and a thickness of 1 in., is taken as the conductivity of the material. In such cases the conductivity is expressed in mohts per square-foot-inch. The symbol K will be used herein to express conductivity.

NOTE.—SOMETIMES IT IS MORE CONVENIENT TO USE CONDUCTIVITIES WHICH ARE EXPRESSED IN MOHTS PER INCH-CUBE (Fig. 120). In any case, it is always necessary to specify the volume unit which is implied when a conductivity value is stated. How these conductivity values are applied in computations is explained in following examples.

EXAMPLES of thermal-conductivity values are given in Table 125 for various common metals, heat-insulating materials, liquids and gases.

123. The Thermal Conductivity Of A Substance Is Not Constant But Varies With The Temperature.—Strictly, values such as those given in Table 125, relate only to one temperature. But they may, without prohibitive error, be used through a reasonably wide range. Usually other variables will introduce greater errors than this variation in K.

EXAMPLE.—The same piece of metal may, under the influence of the same temperature difference, conduct heat more readily when at a high than when at a low temperature. That is, for some substances, it has been found that the value of K changes a certain amount for each change in temperature.

124. To Compute The Value Of "K" At Some Given Temperature When Its Value At Some Other Temperature Is Known the following formula may be used. Note its similarity to For. (96) for computing length of a rod at some given temperature when its length at some other temperature and its expansion coefficient are known. The same general reasoning applies in each case.

(65) $$K_T = K_o\,(1 + kT) \qquad \text{(conductivity)}$$

Wherein: K_T = value of K at any desired temperature. K_o = the known value of K at some other temperature. k = "*temperature coefficient of thermal conductivity*" = the change in value of K for each 1° change in temperature; see note below for some values of k. T = difference between the temperature at which K is known and the other temperature at which K is desired, in degrees.

Note.—Some Values For k with temperatures expressed in degrees Fahrenheit are: Aluminum, 0.000,3. Yellow brass, 0.001,36. Red brass, 0.000,89. Copper, 0.000,03. Cast iron, 0.000,83. Wrought iron, 0.000,1. Lead, 0.000,48.

Example.—At 32° F., K_S for wrought iron is known (Table 125) to be 400 mohts per sq.-ft.-in. What will K_S, for wrought iron, be at a temperature of 182° F.? Solution.—From the preceding note, k for wrought iron = 0.000,1. The *temperature difference* = 182 − 32 = 150° F. Now substitute in the formula: $K_T = K_O(1 + kT) = 400[1 + (0.000,1 \times 150)] = 400\ (1 + 0.015) = 400 \times 1.015 = 406$ *mohts per sq.-ft.-in.*

125. Table Showing Thermal Conductivities Of Various Substances which have been determined by experiment. There is some disagreement between the different authorities as to these values. Further research is necessary to insure complete agreement. (Quoted from various authorities: M = Marks' Mechanical Engineers' Handbook; P = Pender's Electrical Engineers' Handbook, E = Peele's Mining Engineers' Handbook; S = Smithsonian Tables. R = Randall's Practical Heat.)

Material	Ranges through which quoted values of K are fairly accurate		Average working conductivity values (B.t.u. per hour forced through the volume specified by a thermal pressure of 1° F.)	
	Temperatures, deg. Fahr.	Corresponding Range in actual values of Ks	Ks in mohts per sq.-ft.-in	KI in mohts per inch-cube
METALS				
Aluminum	32–500	E 966–1,100	1,050	7.29
Brass, yellow	32–500	E 592– 216	500	3.47
Brass, red	32–500	E 713– 416	600	4.16
Copper	32–500	E 2,080–2,050	2,100	14.59
Iron, cast	32–500	E 507– 205	450	3.12
Iron, wrought	32–500	S 418– 398	400	2.78
Lead	32–500	E 242– 234	240	1.66
Steel, soft	.....	S 322	320	2.22
Zinc	.....	E 433	440	3.05
INSULATING & MISCELLANEOUS				
Air-cell asbestos	212–572	S 0.986–1.45	1.10	0.0076
Asbestos 44 lb./cu. ft.	−300–32	M 1.2 –1.62	1.5	0.0104
Asbestos 29 lb./cu. ft.	−300–32	M 0.654–1.07	1.0	0.0069
Brickdust, course	32–212	M 1.128	1.13	0.0078
Brickwork	68	M 3.42	3.40	0.0236
Cardboard	.....	M 1.44	1.40	0.0097
Cement	95–194	P 2.06 –6.29	4.00	0.0278
Charcoal, powdered	32–212	M 0.635	6.35	0.044
Concrete	68	M 5.22 –5.64	5.50	0.038
Cotton	32–200	M 0.384–0.468	0.45	0.0031
Cork, pulverized	32–200	M 0.252–0.384	0.30	0.0021
Felt	.....	M 0.264	0.26	0.0018
Firebrick	32–2,400	M 9.0	9.0	0.0625
Firebrick, powdered	70–212	M 0.815	0.82	0.0057
Glass, crown, window	.....	M 7.2	7.00	0.0486
Linoleum	68	M 1.28	1.25	0.0087
Magnesia	70–212	M 1.31	1.30	0.0090
Marble	.....	M 20.6	21.00	0.146
Mica	.....	M 5.28	5.25	0.0365
Mill shavings	.....	M 0.6	0.6	0.0042
Paper	.....	M 0.9	0.9	0.0063
Porcelain	.....	M 7.2	7.20	0.0500
Rubber, Para	.....	M 1.31	1.30	0.0090
Sand	68–311	P 2.48 –2.51	2.50	0.0174
Sawdust	70–275	M 0.444	0.45	0.0031
Scale, boiler	.....	R 16.0	16.00	0.111
Slate	.....	M 13.7	14.00	0.0972
Wood ashes	32–212	M 48	0.50	0.0035
Wood, oak, to fiber	68	M 1.44	1.40	0.0097
Wood, pine, to fiber	68	M 1.04	1.00	0.0069
Wool, sheep	68–212	P 0.365–0.441	0.40	0.0028
Wool, mineral	.....	.....	0.42	0.0029
LIQUIDS				
Water	.....	P 3.5–6.5	4.50	0.0312
Brine	39	S 3.35	3.30	0.0229
GASES				
Ammonia	32–212	P 0.133–0.206	0.15	0.0010
Air	32	M 0.151	0.15	0.0010

126. To Compute The Thermal Conductance Of Any Volume Of Any Given Substance, substitute in the following formula, the derivation of which is given below:

$$\mathbf{B} = \frac{K_S A}{L} \qquad \text{(mohts)} \tag{66}$$

and it follows that:

$$K_S = \frac{\mathbf{B}L}{A} \qquad \text{(mohts per sq.-ft.-in.)} \tag{67}$$

or

$$A = \frac{\mathbf{B}L}{K_S} \qquad \text{(square feet)} \tag{68}$$

also

$$L = \frac{K_S A}{\mathbf{B}} \qquad \text{(feet)} \tag{69}$$

Wherein: **B** = thermal conductance, in mohts, as defined in preceding Sec. 120. K_S = thermal conductivity of the substance, in mohts per square-foot-inch; see Table 125 for values. A = area of the substance, taken at right angles to the direction of heat flow, in square feet. L = length or thickness of the substance, in a direction parallel to the direction of heat flow, in inches.

Derivation.—As defined in Sec. 120, the *moht* is the conductance of a body which will permit 1 B.t.u. per hour to flow through it when the thermal pressure is 1° F. It has also been explained that the heat flow through a substance varies: (1) *Directly as the cross-sectional area* (Sec. 115). (2) *Inversely as the length* (Sec. 118). Now the values in the K_S column of Table 125 are the conductances from face to face, in mohts, of slabs, of different substances, 1 sq. ft. in cross-sectional area and 1 in. thick. These values have been determined by experiment. Hence, it follows that if, for any given volume of a certain substance having given dimensions, the K_S value for the substance from Table 124 is multiplied by the sectional area of the volume in square feet and the result then divided by its length (thickness) in inches, the result will be the mohts conductance of that volume when it has the given dimensions. These operations are those which are specified by For. (66).

Example.—What is the thermal conductance in mohts, from face to face, of a slab of wrought-iron boiler plate which is ½ in. thick and 8 sq. ft. in area? Solution.—From Table 125, K_S for wrought iron is 400. Now substitute in For. (66): $\mathbf{B} = K_S A/L = 400 \times 8 \div 0.5 = 6{,}400$ *mohts.*

Note.—If Conductivity Values In Mohts Per Inch-cube Are Used from the K_I column of Table 125, then the equivalent of For. (66) becomes:

$$\mathbf{B} = \frac{K_I A_I}{L} \qquad \text{(mohts)} \tag{70}$$

Wherein: K_I = thermal conductivity of the substance, in mohts per inch-cube. A_I = area of the substance taken at right angles to the direction of heat flow, in square inches. L = length or thickness of the substance in a direction parallel to the direction of heat flow, in inches.

NOTE.—WHEN THE CONDUCTANCE OF A BODY IN MOHTS HAS BEEN DETERMINED, the amount of heat which will flow through it in a given time, under a given thermal pressure or temperature difference, may be computed by substituting in For. (61).

127. A Formula For Computing The Total Flow Of Heat Energy By Conduction Through Any Volume Of A Given Substance, When Its Area, And Length And The Time And Thermal Pressure Are Known is given below. Its derivation follows the formula.

$$(71) \qquad Q = \frac{K_S A(T_2 - T_1)t}{L} \qquad \text{(British thermal units)}$$

Wherein all of the symbols have the same meanings as those specified in Secs. 121 and 126.

DERIVATION.—From For. (61), $Q = Bt(T_2 - T_1)$. But from For. (66): $B = K_S A/L$. Now substituting for B in For. (61), its equivalent from For. (66), there results: $Q = K_S A(T_2 - T_1)t/L$, which is For. (71). Usually, it is preferable to use For. (61) instead of (71), first finding the *mohts conductance* with For. (66).

EXAMPLE.—What quantity of heat will flow, in 1½ hr., through a layer of boiler scale ½ in. thick and 10 sq. ft. in area when the temperature on the outside of the scale is 875° F. and the temperature on the inside of the scale is 375° F.? SOLUTION.—From Table 125, K_S for boiler scale is 16 *mohts per sq.-ft.-in.* Now substitute in For. (71): $Q = K_S A(T_2 - T_1)t/L = [16 \times 10(875 - 375)1.5] \div 0.5 = 160 \times 500 \times 1.5 \div 0.5 = 240{,}000$ *B.t.u.*

128. A Formula For Computing The Rate Of Heat-energy Flow—That Is, The Power Flow—By Conduction through any volume of a given substance is (see derivation below):

$$(72) \qquad B.t.u.\ per\ hr. = B(T_2 - T_1) \qquad \text{(B.t.u. per hr.)}$$

or if, as in electric-furnace and other electrical-apparatus computations, it is desirable to express the rate of heat energy flow in *watts*, then:

$$(73) \qquad Watts = 0.293\ B\ (T_2 - T_1) \qquad \text{(watts)}$$

The thermal conductance of the volume of the substance in question may be computed as explained in Sec. 126.

Derivation.—From For. (61): $Q = Bt(T_2 - T_1)$. Now, to obtain the rate of heat flow per hour, divide For. (61) through by the time in hours, that is by t, thus:

$$(74) \qquad B.t.u.\ per\ hr. = \frac{Q}{t} = \frac{Bt(T_2 - T_1)}{t} = B(T_2 - T_1)$$

Also, since a rate of energy expenditure of 1 *watt* = 3.415 *B.t.u. per hr.*, to convert "*B.t.u. per hr.*" expression of For. (74) into watts, divide by 3.415, thus:

$$(75) \qquad Watts = \frac{B(T_2 - T_1)}{3.415} = 0.293\ B(T_2 - T_1)$$

129. "Thermal Resistance" is, in a sense, the opposite of thermal conductance, which is defined in Sec. 119. While *conductance* expresses the readiness with which a material conducts heat, *resistance* expresses the opposition which a material offers to heat flow. The greater the conductance, the greater the heat flow, but the greater the resistance the less the heat flow.

Note.—Numerically, Heat Resistance Is The Reciprocal Of Heat Conductance And Vice Versa.—That is, if a substance has a heat conductance of 10 *units*, its heat resistance is: $1 \div 10 = 0.1$ *units*. These quantities are analogous respectively to electrical resistance and electrical conductance. Thermal resistance to heat flow is also somewhat analogous to the frictional resistance offered by the interior surface of a pipe to the flow of water through it.

Note.—The Thermal Resistance Of A Substance Is Low if the construction and arrangement of the molecules of the substance is such that heat which is imparted to one part of the substance is transmitted with great rapidity to the molecules in the cooler portions. But if the transmission proceeds only sluggishly, then the resistance is high.

130. Internal Thermal Resistance is the opposition to heat transfer which occurs within the substance. It is, numerically, the reciprocal of internal thermal conductance.

131. External Or Contact—Thermal Resistance is the resistance to heat transfer which occurs between two substances which are in contact with each other. Definite quantitative data relating to this form of resistance are not available.

Note.—Resistance To The Flow Of Heat From The Gases Of Combustion In A Boiler Furnace To The Water In A Boiler is, largely, due to the contact resistance between the gases and the steel boiler-shell or tubes, and between the shell or tubes and the water. It is also due to the internal resistance of the plate itself, the resistance of

a stagnant gas film on one side of the boiler plate, and the resistance of a stagnant water film on the other side.

132. A Unit Of Thermal Resistance Is The "Thom."—This word is merely a contraction of the term "*thermal ohm.*" See, in this connection, Sec. 120 in which the "*moht*" is defined. A body has a resistance of 1 thom when a thermal pressure—or temperature difference—of 1° F. will force heat through it, by conduction, at the rate of 1 B.t.u. per hour.

133. To Compute The Total Heat-energy Flow Through A Substance When Its Resistance, In Thoms, And The Thermal Pressure Are Known, substitute in the following formula, the derivation of which follows from the definition of preceding Sec. 132.

$$(76) \qquad B.t.u.\ per\ hour = \frac{Thermal\ pressure}{Thermal\ resistance}$$

or substituting for the above quantities their equivalents as hereinbefore defined:

$$(77) \qquad B.t.u.\ per\ hour = \frac{(T_2 - T_1)}{\mathbf{R}}$$

Wherein: $\mathbf{R}$ = the thermal resistance, in thoms. The above equation expresses what is sometimes called the *Ohm's law of the heat-flow circuit.* Now if $\mathbf{Q}$ = the total quantity of heat which flows, in B.t.u., it is apparent that:

$$(78) \qquad \mathbf{Q} = \frac{(T_2 - T_1)t}{\mathbf{R}} \qquad \text{(B.t.u.)}$$

EXAMPLE.—A certain slab of copper has a thermal resistance of 0.000,238 thoms. If the temperature on one side of the slab is 42° F., and that on the other is 47° F., what will be the total heat which will flow through it in 2½ hr.? SOLUTION.—Substitute in For. (78): $\mathbf{Q} = [(T_2 - T_1)t]/\mathbf{R} = [(47 - 42)2.5] \div 0.000,238 = 5 \times 2.5 \div 0.000,238 = 52,500$ *B.t.u.* Compare this example with that under For. (61).

134. Thermal Resistivity Is Specific Thermal Resistance.—That is, it is the resistance of a block of the material, which is under consideration, which has a specified length and cross-sectional area. Numerically, a thermal-resistivity value will be the reciprocal of the corresponding thermal-conductivity value. Review Sec. 122 on "Thermal Conductivity." To obtain the thermal resistivities of the materials which are listed in Table 125, in thoms per *square-foot-inch*—or per *inch-*

cube—compute the reciprocals of the corresponding conductivity values there quoted.

Note.—Thermal-resistivity Values Are Not Given In Table 125 because it is usually, when computing, more convenient to use the conductivity values. In many cases, the resistivity values would be long awkward decimals. Equally correct results may be obtained by using either resistivity or conductivity values, if the proper formula is utilized in each case.

135. To Compute The Thermal Resistance Of A Volume Of A Substance In Thoms, first determine its conductance in mohts as specified in For. (66) and then figure the reciprocal of the value thus obtained. This last value will be the thermal resistance, in thoms.

Example.—The thermal conductance of a certain slab of copper is 4,200 mohts. Therefore, *its thermal resistance is:* $1 \div 4{,}200 = 0.000{,}238$ *thoms.*

136. To Compute The Rate Of Heat-energy Flow, That Is, The Power Flow, Through A Substance When Its Thermal Resistance, In Thoms, Is Known, the formulas quoted below may be employed. These, since *resistance* is the reciprocal of *conductance,* follow from Fors. (72) and (73).

$$B.t.u.\ per\ hour = \frac{T_2 - T_1}{R} \tag{79}$$

and

$$Watts = \frac{0.293(T_2 - T_1)}{R} \tag{80}$$

Example.—What will be the heat power loss, in watts, through the heat-insulating jacket of a furnace, if the thermal resistance of the jacket is 0.003 thoms and inside and outside temperatures are respectively 1,700 and 180° F.? Solution.—Substitute in For. (80): $Watts = [0.293(T_2 - T_1)]/R = [0.293 \times (1{,}700 - 180)] \div 0.003 = 0.293 \times 1{,}520 \div 0.003 = 148{,}400$ *watts.*

137. Convection Is Transfer Of Heat By The Flow Of Currents Within A Fluid Body.—The current-flow is due to variations of density, caused by inequalities of expansion and contraction, through the fluid body.

Explanation.—When any portion of a fluid, as air, becomes heated (Fig. 121), it expands, (Sec. 159). The density of that portion of the fluid diminishes. A given volume of it becomes lighter than it was before. That is, the volume of a given weight of the fluid becomes greater. According as the density of any portion of a fluid, as water (Figs. 122, 123,

124, and 125), diminishes, due to conduction of heat to that portion of the fluid, it rises and is displaced by the cooler, more dense and heavier surrounding portions of the fluid. These portions, in turn, likewise become

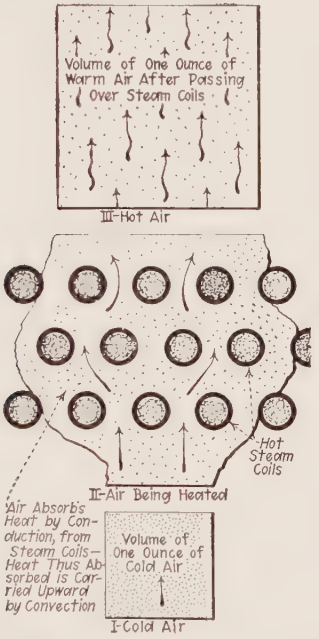

Volume of One Ounce of Warm Air After Passing Over Steam Coils
III-Hot Air
Hot Steam Coils
II-Air Being Heated
Air Absorbs Heat by Conduction, from Steam Coils—Heat Thus Absorbed is Carried Upward by Convection
Volume of One Ounce of Cold Air
I-Cold Air

FIG 121.—Showing the increase in volume of a certain mass (weight) of air in passing over hot steam coils.

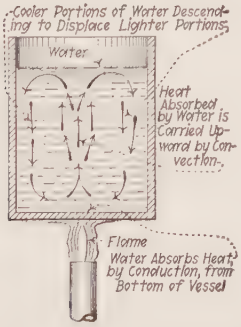

Cooler Portions of Water Descending to Displace Lighter Portions
Water
Heat Absorbed by Water is Carried Upward by Convection
Flame
Water Absorbs Heat by Conduction, from Bottom of Vessel

FIG. 122.—Water circulation when heat is applied to center of a vessel.

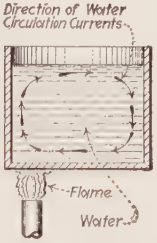


FIG. 123.—Water circulation in vessel heated on one side.

heated and displaced. Continuous circulating currents are thus set up in the fluid. Heat is thereby transferred, by convection, from the parts of

the containing vessels which are in direct contact with the sources of heat to the parts which are remote therefrom.

Hot water is admitted (Fig. 126) to a cold cast-iron radiator, *R*. The

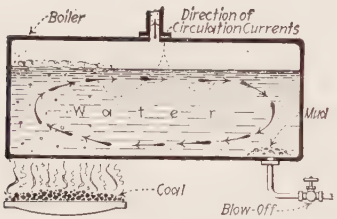


Fig. 124.—Showing water circulation in ordinary cylindrical drum boiler.

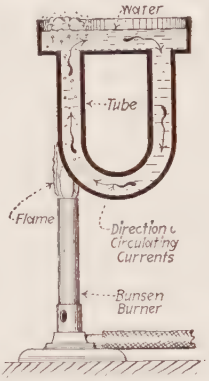


Fig. 125.—Showing circulation in a U-tube when one leg is heated.

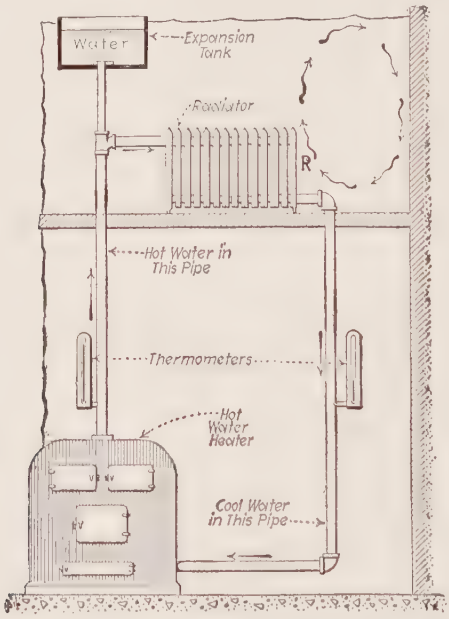


Fig. 126.—Hot-water heating system.

heat in the water is transferred, by conduction, to the iron walls of the radiator. Then the heat in the iron is transferred, by conduction, to

the particles of external air which are directly in contact with the radiator. This air expands. Its density diminishes. It becomes lighter, per unit of volume, than it was a moment previous. It is displaced from contact with the radiator by the heavier air below it. Similarly other portions of air become heated, expanded, diminished in density and displaced from contact with the radiator. A continuous convection-current, which carries the heat to the parts of the enclosed space which are remote from the radiator is thus set up. This current constantly imparts its heat, by conduction, to the remote bodies with which it makes contact, and constantly returns to the radiator for a fresh supply. Some heat is also transmitted from a radiator by *radiation* (Sec. 138).

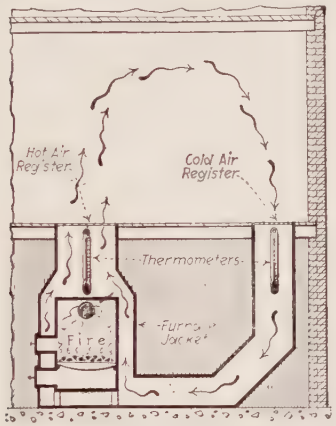


FIG. 127.—Heating with a warm-air furnace.

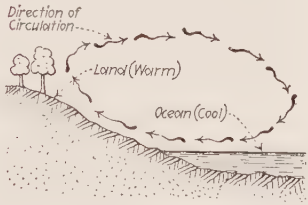


FIG 128.—Showing convection currents of air at junction of ocean and land. (Direction of flow may be reversed when the land is the cooler.)

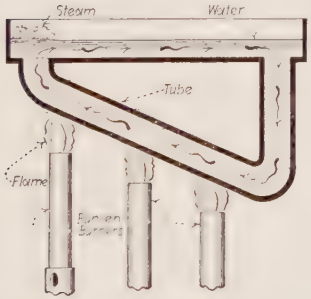


FIG. 129.—Showing circulation in inclined tube.

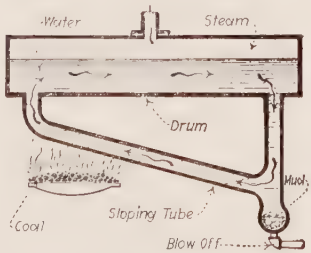


FIG. 130.—Showing water circulation in simple water-tube boiler.

NOTE.—TRANSFER OF HEAT BY CONVECTION IS UTILIZED IN MANY WAYS.—The effectiveness of hot-water (Fig. 126), steam, and hot-air (Fig. 127) heating systems (Div. 17), of ventilating systems, and of chimneys and stacks (Sec. 256) depends upon this principle. To it, also,

are due the winds (Fig. 128) which traverse land and sea. Convection is of fundamental importance in the operation of steam boilers. The tubes of horizontal water-tube boilers are set (Figs. 129 and 130) at an inclination to the horizontal. The object is to facilitate transfer of heat by convection. Rapid circulation of the water-currents, and, therefore, of heat-transfer by convection is (Figs. 131 and 132) one of the foremost considerations in boiler design. The

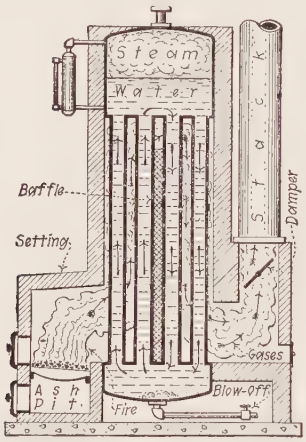


Fig. 131.—Water and gas circulation in one type of vertical water-tube boiler.

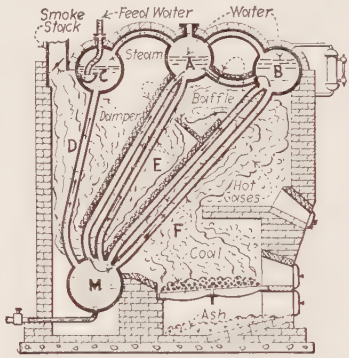


Fig. 132.—Showing water and gas circulation in Stirling-type boiler.

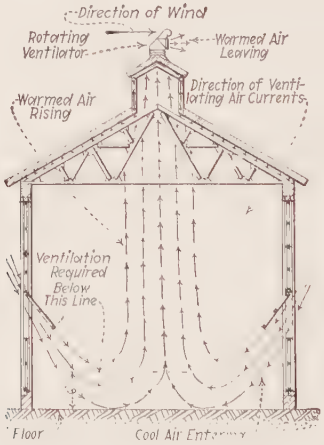


Fig. 133.—Ventilation due to convection. (This shows a scientific arrangement. Note movement of air near floor where employes work. The wind, if there is any, assists in promoting circulation.)

principle of convection is, often, utilized (Fig. 133) in the natural ventilation of buildings.

Note.—The Mathematics Of Heat Transfer By Convection Is Rather Complicated.—It involves consideration of many factors, as temperatures, specific heats, densities, viscosities, and probably others. Hence, no formulæ pertaining to this subject will be given herein. How a chimney produces *draft* by convection is explained in Sec. 256 and in the author's Steam Boilers.

138. Radiation Is Transfer Of Heat From One Body To Another By Wave Motion In The Æther (Sec. 46). When being thus transferred by wave motion in the æther, the energy is called radiant heat energy or merely radiant heat. Radiant heat is, therefore, wave motion and not molecular motion as is heat in its most common form. The earth receives the sun's heat by radiation. The æther which fills interstellar space, and, in fact, all space unoccupied by matter, is the medium of transmission.

Explanation.—If the bare hand be suddenly thrust before the open door of a boiler-furnace, within which an intensely hot fire is burning, an unbearable sensation of heat will be felt instantly. Evidently, this can be due neither (Sec. 137) to convection nor (Sec. 111) to conduction. It cannot be accounted for on the principle of convection, because the convection-current flow will be inward, instead of outward, through the furnace-door. The exposed hand will be constantly bathed by an air-current flowing into the furnace from the comparatively cool atmosphere of the room. For the same reason, the intense sensation of heat cannot be accounted for on the principle of conduction. Even if the air in contact with the hand were to become temporarily stagnant, a considerable interval of time would still be required for it to conduct the heat thereto, because air is (Sec. 114) a poor conductor of heat.

The true explanation is, that the vibratory heat motion, of the molecules of the combustibles in the furnace, sets up a wave motion in the æther which (Sec. 46) fills the interstices between the air molecules. These heat waves travel, at enormous speed (Sec. 178), along straight lines which radiate in all directions from the source of heat. They tend to reproduce (Sec. 142), in all matter which lies in their path, the vibratory heat motion of the heated substance wherein they originate. Those which travel in the direction of the exposed hand before the furnace door, traverse the intervening distance in an interval of time which is so brief as to be virtually instantaneous. In fact, radiant heat waves travel at the same speed as do light waves, viz.: 186,000 miles per sec., as explained in Sec. 178.

139. Heat May Be Radiated Through Vacua.—The heat energy of the sun passes through a presumably perfect vacuum, millions of miles in extent, before it reaches the earth's atmosphere.

Note.—Heat Can Neither Be Conducted Nor Convected Through A Vacuum.—In a space wherein matter is nonexistent, both the molecular motion by which heat is conducted, and the current-flow by which it may be convected, must likewise be nonexistent.

Example.—A glass vessel enclosing a practically perfect vacuum might be interposed between the bare hand and the fire in the furnace. But the sensation of heat would still be felt.

140. Heat Waves May Be Visible Or Invisible.—Those which are visible are (Sec. 176) classed as light waves. The quality of visibility depends upon the degree of heat (temperature) which is possessed by the bodies from which the waves emanate.

Example.—A mass of iron when heated to about 480° F. will, in a dark room, give off visible heat waves. When the temperature of the iron drops below 480° F., the heat waves will become invisible.

141. Heat May Be Radiated Through Transparent Or Translucent Bodies To Other Bodies Beyond.—Some substances tend (Sec. 143) to absorb heat waves more readily than do certain other substances.

Fig. 134.—Lens of ice shaped like a burning glass concentrates radiant heat waves of sun and ignites paper.

Example.—The visible heat waves, which (Fig. 134) are manifested in the sun's rays, tend to stimulate heat motion in the lens-shaped cake of ice. Presently the ice lens will be melted to water. But while the lens continues intact, the heat waves passing through it will, by being focused or concentrated on the faggots, ignite them.

142. Radiant Energy Is That Form Of Energy Which Resides In Æthereal Heat Waves.—It is the essence of the

phenomenon which (Sec. 138) is conveniently defined as transfer of heat by radiation, or as *radiant heat.*

Explanation.—The earth receives the sun's heat by radiation. But the sun's heat exists as a vibration of the molecules of the sun's substance. This vibratory molecular motion, or heat, cannot be imparted by conduction to the æther which lies between the sun and the earth and thence to the molecules of the earth's substance—the æther has no molecular structure to receive it. Therefore, it is an obvious misnomer to consider the phenomenon of radiation as a direct transfer of actual heat by contact.

The energy of the sun's molecular vibration, or heat, is, however, imparted to the æther. This transfer of energy is manifested by waves which are thereby made to traverse the æther. These waves radiate from the sun along straight lines (Sec. 138). They are waves of radiant energy. When a mass of matter, as the earth, intercepts their path, they impress their radiant energy or a portion of it on that mass of matter and thereby reproduce therein the molecular motion, or heat, to which they owe their origin.

143. Waves Of Radiant Energy Are Converted Into Heat In The Material Bodies Which Intercept Them.—Radiant energy tends, more or less, to penetrate (Sec. 141) substances which are transparent, translucent or opaque to light, as respectively a window-pane, a draftsman's celluloid triangle, or a china cup. The ability of any of these substances to convert radiant energy into heat is inversely proportional to its capacity for transmitting light. An ideally transparent substance would convert none of the radiant heat energy which impinged on it to molecular-vibration heat energy; all would pass through. An absolutely opaque non-reflecting substance would convert all radiant energy which impinged on it to molecular-vibration heat energy. Radiant energy cannot penetrate substances into which light cannot enter. The radiant energy, or a portion of it, is transformed into heat among the surface molecules of such substances. Then the heat is carried, by conduction, throughout the body of the substance. The more impenetrable the substance, the greater its capacity for conversion of radiant energy into heat.

Note.—Dull Black Surfaces Of Bodies Are The Best Converters Of Radiant Energy.—They are also the best radiators thereof. It is presumed that if a surface, in which the qualities of blackness and dullness would be perfectly blended, could be prepared, the surface would absorb, and convert into heat, all of the radiant energy which it might

intercept. A surface coated with lampblack is probably the nearest approach to the ideally perfect absorbing surface.

144. Radiant Energy Which Is Intercepted By A Material Body May Be Reflected Therefrom (Figs. 135, 136 and 137). Some of the heat waves which impinge upon the surface of the body will (Sec. 138) become transformed into molecular motion or heat. But others may rebound. *The angle of incidence, I,* (Fig. 135) is always equal to *the angle of reflection, R.*

Note.—Brightly Polished Surfaces Reflect Radiant Energy Very Readily.—Thereby they tend to prevent the absorption of radiant heat by any body which they surround. Conversely, polished surfaces are poor radiators of heat thereby they tend to prevent loss of

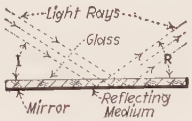


Fig. 135.—Heat waves are reflected in the same manner as are light waves.

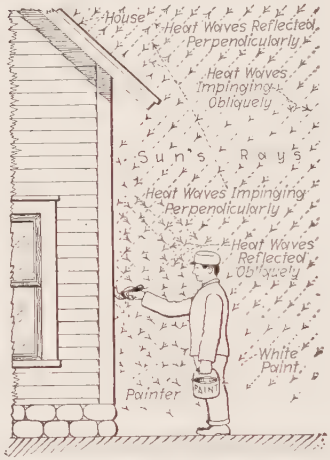


Fig. 136.—Reflected radiant energy from the sun makes it hot for the painter.

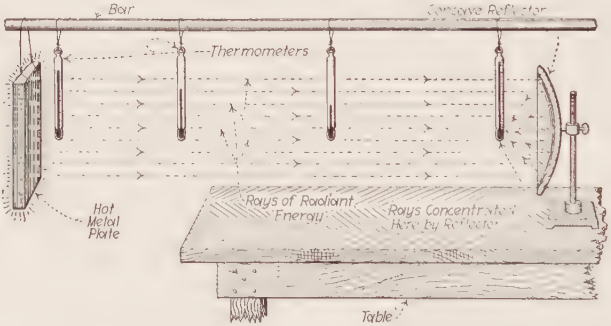


Fig. 137.—Radiant-energy heat rays are reflected and focused by a concave mirror in the same manner as are light rays.

radiant heat from bodies which they surround. A bright silvery surface (Figs. 135 and 137) will reflect most of the radiant energy which it may

intercept. A white painted surface (Fig. 136) would, by reflection, produce a much more uncomfortable heating effect than would a black surface.

145. Surfaces Which Are Good Radiators Of Radiant Heat Are Also Good Absorbers Thereof. Surfaces Which Are Poor Radiators Are Good Reflectors.—These facts may (Figs. 138 and 139) be readily demonstrated by experiment. Advantage of them is taken in many practical applications.

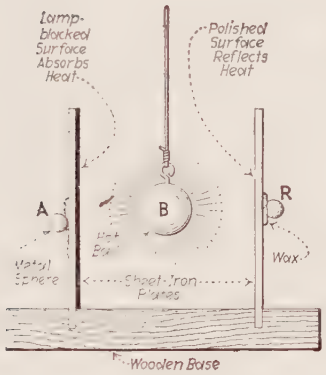


FIG. 138.—Good heat reflectors are poor heat absorbers and vice versa.

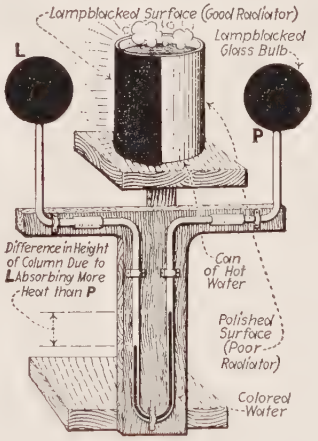

Lampblacked Surface (Good Radiator)
Lampblacked Glass Bulb
L
P
Difference in Height of Column Due to L Absorbing More Heat than P
Can of Hot Water
Polished Surface (Poor Radiator)
Colored Water

FIG. 139.—Good heat absorbers are good heat radiators.

In general, the rough dark surfaces are good radiators and absorbers; smooth polished light surfaces are good reflectors and poor absorbers.

EXAMPLE.—In Fig. 138, the metal sphere, *A*, on the lampblacked plate will melt off before that, *R*, on the polished plate melts off. The lampblacked plate quickly absorbs radiant heat from the hot metal ball, *B*. The polished plate reflects the heat away. In Fig. 139, the bulb, *L*, absorbs more heat than does *P*, because the lampblacked side of the hot-water-can radiates heat much more rapidly than does the polished side.

EXAMPLE.—The metal casings of "thermos" bottles (Figs. 106 and 107) are often nickeled and polished on the outside to minimize the loss or gain of heat by them by radiation. The glass container inside such a bottle is similarly coated like a mirror for the same reason. Likewise calorimeter vessels (Fig. 95) are, usually, of polished nickel. Electric heaters (Fig. 82) have highly polished reflectors. Steam-heating-system

radiators (Sec. 590) are, purposely, left rough outside to promote radiation of heat from them.

146. Radiant Energy Is Susceptible To Refraction.—This is observed when visible heat waves, in the form of rays of sunlight, are (Figs. 134 and 140) caused to pass through a convex lens. A refractive, or bending, effect is also observed (Figs. 141 and 142) when visible heat waves, or light rays, pass through the bounding surfaces of transparent substances, as clear water or glass.

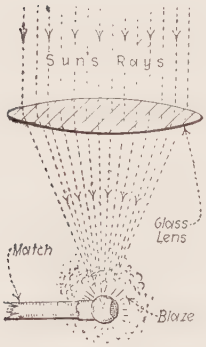


Fig. 140.—Sun's rays are refracted by the lens and concentrated on the head of a match, igniting it.

Note.—Radiant Heat Waves May Therefore Be Concentrated With A Lens (Figs. 134 and 140) in about the same way that light waves can be concentrated.

147. The Radiant Heat Which Is Given Off By A Body may be computed by the Stefan-Boltzmann formula, which is as follows:

$$Q = kAt\left(\frac{T}{100}\right)^4 \qquad (81)$$ (British thermal units)

Wherein: Q = the quantity of heat, in British thermal units, which is radiated. k = a constant for the material, taken from Table 149. A = the area of the radiating surface, in square feet. t = the time interval, in hours, during which the radiation occurs. T = the absolute temperature

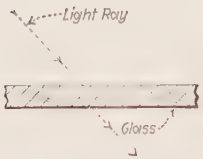


Fig. 141.—The course of a ray of light is changed by refraction when it passes through the common surface of two transparent mediums of different density.

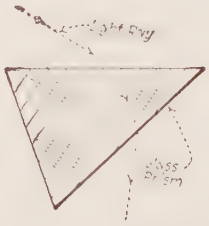


Fig. 142.—Path of a light ray is deflected when passing through a prism.

of the body, in degrees Fahrenheit = reading of the observed temperature + 460.

For a radiator possessing absolute blackness, For. (81) becomes:

$$(82) \qquad Q = 0.161{,}84t\left(\frac{T}{100}\right)^4 \qquad \text{(British thermal units)}$$

148. The Net Heat-transfer, By Radiation, Between A Hot Surface And A Parallel Cool Surface (both surfaces must be very large, of the same size, and one of them a perfectly black body, Fig. 143) may be computed by the following adaptation of the Stefan-Boltzmann formula:

$$(83) \qquad Q_R = k\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] \qquad \text{(B.t.u. per hr. per sq. ft.)}$$

Wherein: Q_R = quantity of heat transferred, in British

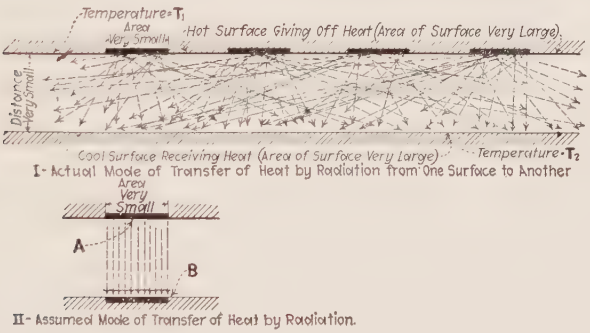

Temperature=T1
Area Very Small
Hot Surface Giving Off Heat (Area of Surface Very Large)
Distance Very Small
Cool Surface Receiving Heat (Area of Surface Very Large)
Temperature=T2
I- Actual Mode of Transfer of Heat by Radiation from One Surface to Another
Area Very Small
A
B
II- Assumed Mode of Transfer of Heat by Radiation.

FIG. 143.—Showing how heat actually radiates, and how, for the purposes of computation, it is assumed to radiate. (In *II* it is assumed that all heat is radiated at right angles to the surfaces. This is assumed to be true only when the surfaces are very large.)

thermal units, per hour per square foot of area (*A* or *B*, Fig. 143) of either surface. k = a constant for the material, taken from Table 149. T_1 and T_2 = respectively, the absolute temperatures in degrees Fahrenheit, of the hot and cold surfaces = reading of the observed temperature of each surface + 460. This formula illustrates the principal of mutual radiation. However, in practice very few cases arise in which the radiation is between two large parallel surfaces of equal area, one of which is a perfectly black body. Hence, the formula can seldom be used for accurate solutions. But

it can be used in most cases, such as in boiler furnaces, for calculating approximately the heat which radiates from a square foot of an incandescent body.

149. Table Showing Values Of The Radiation Constant k For Various Materials (From Marks' Mechanical Engineers' Handbook).

Material	k	Temp., deg. Fahr.	Material	k	Temp., deg. Fahr
Ideally black body	0.1618	70	Zinc, dull	0.034	120–545
Glass, smooth	0.154	.....	Cast iron, rough, highly oxidized	0.157	105–480
Brass, dull	0.0362	100–660	Lime plaster, rough white	0.151	150–195
Lampblack	0.154	32–100	Slate, smooth	0.115	140–400
Copper, slightly polished	0.0278	100–540	Field soil	0.063	140–400
Wrought iron, dull, oxidized	0.154	70–670	Water	0.112	140
Wrought iron, (ordinary black body)	0.0562	85–225	Ice	0.106	32
Wrought iron, highly polished	0.0467	105–480	Incandescent bodies	0.155	

150. Radiant Heat Within A Boiler Furnace will now be considered. A boiler receives little heat by radiation from the gases of combustion. It may receive some heat by radiation from the long tongues of luminous flame which result from burning highly volatile bituminous coals. But most of the heat delivered to a boiler by radiation comes from the glowing and incandescent fuel on the grate, and from the highly heated fire-brick lining of the furnace. For a given grate area neither the contour of the portion of the boiler surface which receives the radiant heat, nor (within reasonable limits) the distance of the surface from the fuel bed, have any apparent influence on the amount of heat thus transferred to the boiler shell by radiation.

Example.—The temperature of the incandescent fuel bed, and of the fire-brick lining, in a boiler furnace, is 2,300° F. The temperature of the boiler shell is 600° F. If the furnace temperature be raised to 2,500° F., what will be the increase in the quantity of heat transferred to the boiler shell by radiation? Solution.—k for wrought-iron bodies (Table 149) = 0.154. By For. (83), *the heat radiated under the prevailing furnace temperature* $Q_R = k\,[(T_1/100)^4 - (T_2/100)^4] = 0.154 \times \{[(2{,}300 +$

460) ÷ 100]^4 − [(600 + 460) ÷ 100]^4} = 87,400 *B.t.u. per hr. per sq. ft. of the area of the hot surface which radiates the heat.* Also, by For. (83) *the heat which would be radiated under the increased furnace temperature* = $Q_R = k\,[(T_1/100)^4 - (T_2/100)^4] = 0.154 \times \{[(2{,}500 + 460) \div 100)]^4 - [(600 + 460) \div 100]^4\} = 116{,}300$ *B.t.u. per hr. per sq. ft. of the area of the hot surface which radiates the heat.* Hence, *the increase in the quantity of heat radiated* = 116,300 − 87,400 = 28,900 *B.t.u. per hr. per sq. ft. of the area of the hot fuel bed.*

151. The Problem Of Heat Radiation In Boiler Furnaces Is Very Complicated.—This is particularly true of the radiation which occurs in the furnaces of externally fired boilers. It is beyond the province of this book to go into the abstruse mathematics of the subject. Enough has been shown, however, in the preceding example to emphasize the advantage, in boiler operation, of maintaining high furnace temperatures. As indicated in the solution of the preceding example, the quantity of heat which a boiler receives by radiation increases very rapidly as the furnace temperature rises.

Examples.—By increasing the furnace temperature from 2,000° F. to 3,000° F., the quantity of heat which is delivered to a boiler by radiation under the lower temperature, may be increased approximately four times. By permitting the temperature to fall from 2,500° F. to 2,400° F., the quantity of radiant heat may be diminished about 12 per cent. The fusing temperature of the ash generally limits the maximum attainable temperature of the fire in a boiler furnace.

152. Heat Transfer May Be Effected By Simultaneous Occurrence Of Conduction, Convection And Radiation.—When the three modes of heat-transfer thus act conjointly to deliver heat to a substance, the resulting phenomena are very complicated and difficult of exact analysis.

Explanation.—In boiler operation, the furnace heat (Fig. 144) is transferred by convection and radiation to the surface of a stationary gaseous film which blankets the heating surface of the boiler. Or, perhaps, a coating of soot may interpose between the film of gas and the heating surface. The heat is then carried by conduction to the water in the boiler. It traverses the external film of gas, the coating of soot, the boiler plate, perhaps a layer of scale on the inner surface of the plate, and, finally, a film of stagnant water and steam before it passes into the mass of moving water in the boiler. During the progress of the heat flow from the outer surface of the external gaseous film to the moving water in the boiler, the mode of transfer alternates successively between

external and internal (Sec. 112) conduction. When the heat is finally conducted into the moving water, the convection currents circulating therein distribute it throughout the mass.

Now, heat is not transferred as readily by external conduction as by internal conduction. Also, the rate of transfer by external conduction seems to vary, more or less, according to the various natures of the sub-

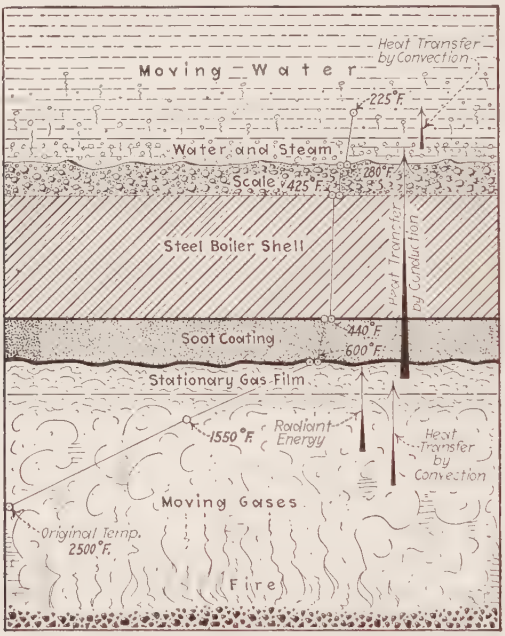


Fig. 144.—Diagrammatic representation of heat transfer in a boiler and furnace.

stances in contact. This introduces a factor that must be variously reckoned with where (Fig. 144) a series of dissimilar substances are successively in contact.

The rate of heat transfer by convection, both in the furnace and in the boiler, will be considerably modified by the velocity of flow of the furnace gases and of the water. As the velocity flow of either of these mediums increases, the thickness of the film of stagnant gas which blankets the heating surface externally, or of the film of stagnant water which adheres to the plate internally, will be materially diminished. These films are relatively poor conductors of heat.

It is evident, therefore, that the quantity of heat which may be transmitted, through the external film, from the convection currents in the furnace, and, through the internal film, to the convection currents

in the boiler, will be greatly modified according to the thickness of the films.

The transfer of heat by radiation will, likewise (Sec. 143) be governed by variable conditions.

QUESTIONS ON DIVISION 5

1. What are the three modes of heat transfer?
2. State an instance wherein the three modes of heat transfer occur simultaneously.
3. What change in the motion of the molecules of a substance occurs when the substance is heated?
4. What is *heat conduction*? Give an example.
5. Why does the protruding end of a bar of iron remain cool while the other end is being heated in a forge fire?
6. What is *internal conduction*? *External conduction*? Give some examples of each.
7. What factors determine the flow of heat through a substance?
8. Explain the fundamental cause of the warmth which a blanket of snow secures to vegetable life.
9. In what ways do the elements of time and distance affect the rate of heat transfer between two points in any substance?
10. What is *thermal conductance*?
11. Why do not all materials conduct heat at the same rate?
12. What is the name of the unit of thermal conductance? Of thermal resistance? What is the value of each of these units?
13. What is *thermal conductivity*?
14. In what manner do temperature changes affect the thermal conductivities of substances?
15. What is *internal thermal resistance*? *External thermal resistance*?
16. What is *thermal resistivity*?
17. What should be the intrinsic properties, with respect to heat-effects, of the materials used in making an ice-box or a fireless cooker?
18. By what quantitative units are resistivity and conductivity expressed mathematically? Explain the meaning of each unit.
19. Explain the mutual relation existing between the British thermal unit and the units of conductivity and resistivity.
20. What is *convection*?
21. Explain the phenomena of convection in hot-water and hot-air heating systems and in ordinary stove heating.
22. Why are the tubes in horizontal water-tube boilers set sloping?
23. What is *radiation*?
24. Wherein does radiation chiefly differ from conduction and convection?
25. In what manner does the earth's atmosphere become heated by radiant energy from the sun?
26. What is *radiant energy*?
27. What is the velocity of radiant energy?
28. What characteristic must a substance possess in order that radiant energy may pass through it?
29. In what manner is a body heated by radiant energy?
30. Describe how radiant energy may be reflected.
31. Give some examples of refracted radiant energy.
32. What characteristic should a substance possess to render it a perfect absorber of radiant energy?
33. What kind of surface is best for radiating heat?
34. What material affords the closest approximation to the ideally perfect absorber of radiant energy?
35. What are the sources of radiant heat in the furnace of an externally fired boiler?

36. What circumstance generally limits the maximum temperature that may be realized in a boiler furnace?

37. In what manner does the velocity of the flow of gases in a boiler furnace chiefly affect the transfer of heat from the gases to the boiler?

PROBLEMS ON DIVISION 5

1. A body having a cross-sectional area of 5 sq. in. conducts 41 B.t.u. of heat per min. What would be the rate of heat conduction of a body of the same substance having a cross-section of 6.5 sq. in.?

2. If one end of an iron rod is heated to 500° F. in a forge fire, while the temperature of the opposite end is 100° F., what is the thermal pressure between the two ends?

3. The temperature of one end of a stone column is 300° F. The temperature of the opposite end is 70° F. The quantity of heat flowing, in 5 hr., between the two ends is 700 B.t.u. What is the conductance of the column?

4. A body has a conductance of 11 mohts. What thermal pressure will force 8,720 B.t.u. through the body in an hour and ten minutes?

5. The side sheets of the fire-box of a steel boiler are 0.5 in. thick. The area of each sheet is 30 sq. ft. What is the thermal conductance from the fire surface to the water surface of each sheet?

6. A steam pipe is covered with a 4-in. thickness of mineral wool. The length of the covering is 20 ft. Its mean diameter is 6 in. The temperature of the pipe is 300° F. The temperature of the surrounding air is 90° F. What quantity of heat flows, in 10 hr., through the covering?

7. A clean steel boiler tube has a thermal resistance of 0.000,267,2 thoms. If the average temperature on the fire side of the tube is 1,500° F., and on the water side 310° F., how much heat will flow through it in 5 hr.?

8. A brick wall is 9 in. thick. What is the thermal resistance through each square foot of its area?

9. The side wall of a brick boiler-setting is 6 ft. high, 15 ft. long and 15 in. thick. The average temperature on the furnace-face of the wall is 2,000° F., and on the outer face, 190° F. What is the heat-power loss through the wall?

10. The white-hot fuel in the fire-box of a locomotive-type boiler is at a temperature of 2,400° F. The crown-sheet temperature is 700° F. If the fire temperature is raised to 2,600° F., how much more heat per hour will the crown-sheet receive by radiation from the fire?

DIVISION 6

EFFECTS OF HEAT

153. The Three Possible Effects Of Adding Heat To A Substance Or Abstracting Heat From It were stated in Sec. 54, as (1) *Change of temperature.* (2) *Change of state.* (3) *External work.* In this division, it will be shown what changes in bodies may accompany these three fundamental effects of heat transfer. Some of these changes will then be treated more in detail in following divisions. In all cases, the aim shall be to discuss principally such changes as affect practical applications of heat, such as power plants, heating of buildings, refrigeration, and industrial systems generally.

NOTE.—THE ADDITION OR ABSTRACTION OF HEAT CHANGES THE "PROPERTIES" OF A SUBSTANCE AND THEREBY PERFORMS "PROCESSES."—A *property of a substance* is any characteristic of the substance which may be used to describe the substance or to describe what the substance is capable of doing—some properties are shape, size, density, temperature, state, taste, color, odor, solubility, strength, electric resistance, thermal resistance, chemical composition. A *process* is simply a change in one or more of the properties of a substance. In this division will be discussed some of the processes which accompany the addition of heat to or the abstraction of heat from substances. Also, since "change of temperature" is a process which frequently accompanies the addition or abstraction of heat, the influence of temperature on the other properties of substances will be discussed. The processes and properties which will be treated include: (1) *Expansion and contraction,* Secs. 159 and 160, also treated in detail by Div. 7. (2) *Melting,* Sec. 161, also treated in detail by Div. 9. (3) *Vaporization,* Sec. 162, also treated in detail by Div. 10. (4) *Sublimation,* Sec. 163. (5) *Chemical combination, decomposition, and dissociation,* Secs. 155 to 158. (6) *Viscosity,* Sec. 165. (7) *Absorption,* Sec. 168. (8) *Solution and solubility,* Secs. 168 to 174. (9) *Electric resistance,* Sec. 182. (10) *Strength,* Sec. 184. (11) *Capacity for emitting radiant energy,* Sec. 176.

154. A "Physical Process" is any change which a substance is made to undergo *without alternation of the arrangement of the atoms which compose its molecules.* Very frequently physical

processes are the effects of heat addition or abstraction. Some examples of physical processes are: (1) *Change in temperature.* (2) *Change in volume.* (3) *Change in state,* as from solid to liquid or from liquid to gaseous. (4) *Absorption* (Sec. 168). (5) *Solution* (Sec. 170).

Note.—Physical Processes May Be "Reversible" Or "Irreversible" depending on whether, after a process is completed, the substance can be returned readily to its original condition. *Most physical processes are reversible.* Thus, water may readily be cooled after being heated or it may readily be condensed after being vaporized into steam. *Some physical processes are, however, irreversible.* Thus, if a 12-ft. board is cut into two 6-ft. lengths, it cannot again be made into a 12-ft. board.

155. A "Chemical Process" or Reaction is a change which a substance is made to undergo whereby its chemical composition (*the arrangement of the atoms in its molecules*) is altered. Chemical processes are, in general of four kinds: (1) *Combination,* wherein 2 or more substances combine to give 1 substance. (2) *Decomposition,* wherein 1 substance is changed into 2 or more substances. (3) *Displacement,* 1 element and 1 compound combine to give 1 other element and 1 other compound. (4) *Double decomposition,* wherein 2 compounds give 2 different compounds. Nearly all chemical processes are attended by the liberation or continual absorption of heat.

Examples.—If a strip of magnesium is lighted with a match, it takes fire and "burns" with a white flame. This (and every other) burning is actually a chemical combination of the material burned and oxygen from the air. If some mercuric oxide (red oxide of mercury) is heated in a test tube, globules of mercury will deposit on the cooler walls of the tube and oxygen (gas) will pass out of the tube—a lighted match placed in the mouth of the tube will glow in the oxygen. The mercuric oxide is "decomposed" into mercury and oxygen. If some bits of zinc are placed in a tube with some dilute hydrochloric (muriatic) acid, a gas will be evolved at the surface of the zinc. This gas will be found to burn with a pale blue flame—it is hydrogen. Here "displacement" occurs—the zinc (element) and the acid (compound) react to form hydrogen (element) and zinc chloride (compound). In the purification of water, a solution of lime (calcium hydroxide) and a solution of ferrous sulphate (copperas) are frequently introduced into the water which is to be purified. These two compounds, by "double decomposition," form ferrous hydroxide and calcium sulphate—the hydroxide forms into small flakes which slowly settle and carry with it the impurities which may be in the water. More examples of chemical reactions are given in succeeding sections.

Note.—The Distinction Between A "Chemical" And A "Physical" Process is this: Chemical processes have to do only with changes in the arrangement of the atoms within the molecules, whereas physical processes have to do only with changes exterior to the construction of the molecules. This distinction is important.

156. Dissociation Is A Reversible Decomposition.—Not all decompositions are reversible. If a piece of wood is heated

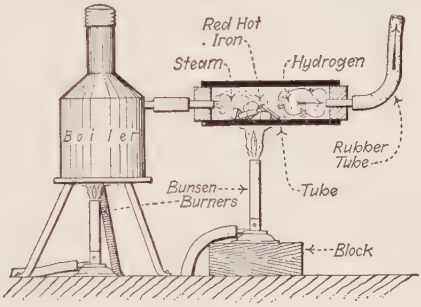


Fig. 145.—Decomposing water into hydrogen and oxygen—oxygen unites with hot iron forming iron oxide. Heat must be supplied, however, to maintain the decomposition. Hence, the heat is "absorbed" in the process.

in a closed vessel (so that no air can reach the wood), the piece will be decomposed, by the absorption of heat, into charcoal

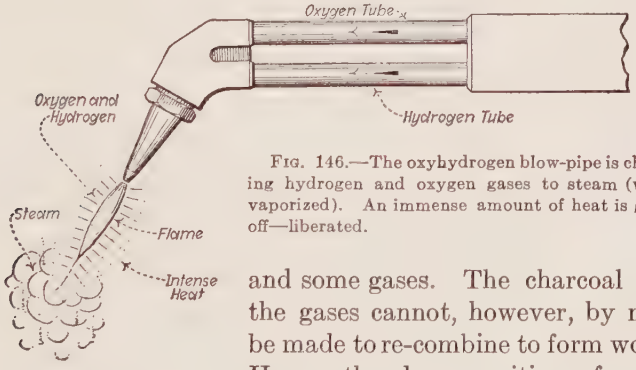


Fig. 146.—The oxyhydrogen blow-pipe is changing hydrogen and oxygen gases to steam (water vaporized). An immense amount of heat is given off—liberated.

and some gases. The charcoal and the gases cannot, however, by man be made to re-combine to form wood. Hence, the decomposition of wood is *irreversible*. On the other hand, however, water can be decomposed (by an electric current or by heating to a very high temperature) into two gases, hydrogen and oxygen (Fig. 145). These gases will again combine, if mixed and ignited, to form water (Fig. 146). During the combination, as much

heat is liberated as was absorbed when the water was decomposed. Hence, the decomposition of water is a *reversible chemical process.*

157. The Addition Of Heat Energy Is Necessary To Effect Certain Chemical Processes. However, Heat Energy Is Liberated By Most Chemical Processes.—As was explained in Sec. 28, energy of some sort is either required to effect or is liberated by every chemical process or reaction. It is the purpose here to give consideration to those chemical processes whereby only one kind of energy, *heat energy*, is either absorbed or liberated. Those chemical changes in which heat energy is liberated are called *exothermal processes.* Those in which heat energy is continuously absorbed are called *endothermal processes.* The amount of energy which is absorbed or liberated by the different chemical processes is usually determined initially by experiment; values are given in chemistry books and in handbooks such as the "Smithsonian Institute Tables." The amount of heat energy liberated or absorbed by a chemical reaction may in many cases, be determined with a calorimeter; see Sec. 456. The absorption or liberation of heat are not necessarily evidences of chemical processes. All physical processes are similarly accompanied by heat transfers. Examples are heating due to rubbing or percussion and the heat released or absorbed during changes of state (Sec. 54) of matter.

Explanation.—One pound of every substance (at a given temperature and under a given pressure) contains: (1) *A certain definite amount of chemical energy.* (2) *A certain definite amount of matter.* See Sec. 28. The amount of matter in the substance can be determined quite accurately by weighing. But there is no way in which the *total* amount of chemical energy in it can be determined. This chemical energy was imparted to the atoms of the substance both when they were first evolved and possibly, also at later times, whenever the atoms were parties to chemical reactions. Thus chemical energy, of an unknown amount, normally resides "bound in" or latent in every substance.

However, if a chemical process occurs whereby the molecules of given weights of two or more substances are disrupted into their constituent atoms which atoms then recombine to form the molecules of a new substance or substances, *a definite amount of energy is either absorbed or released* during the process. The amount of heat energy (in, say, British thermal units) which will be absorbed or released by any chemical reac-

tion between given weights of two or more substances must, apparently, be determined by experiment; there seems to be no way, except in certain special cases, to compute it. In most cases, the energy is thus absorbed or liberated as heat energy. If heat energy is absorbed, it is automatically transformed into chemical energy which then resides latent within the new substance or substances. If heat energy is liberated, it is energy which was transformed from part of the chemical energy which formerly resided—latent—within the original substances. Examples of the amounts of heat energy thus absorbed or liberated by certain chemical reactions are given below.

Hence, it is evident that if heat energy is liberated by a chemical reaction, this energy is part of the store, of unknown amount, of chemical energy which formerly resided within the molecules of the substances. Possibly a part of the liberated heat is derived from each of the original substances which were parties in the reaction. If heat energy is absorbed by a chemical reaction, the energy thus added goes to increase the store of chemical energy in the molecules of the resulting substance or substances. Somehow or other, chemical energy is necessary to "hold" the atoms in the molecules, different amounts of it being necessary for different kinds of atoms and molecules. So when the molecular structure—the substance—is changed, the chemical energy must be either released or absorbed.

When a compound is decomposed into its constituent elements, the amount of heat absorbed or liberated is exactly the same as that which was evolved or absorbed in the original formation of the compound. When both combination and decomposition are involved in a complex chemical change, the heat liberated or absorbed is the net result of the two reactions.

EXAMPLE.—When water is decomposed, see equations below (Fig. 145), by any process whatsoever, into oxygen and hydrogen, heat energy is absorbed. When oxygen and hydrogen combine (Fig. 146), as in combustion, much heat energy is liberated.

158. Thermochemical Equations are equations which show not only the chemical reaction of a process but which also show the amount of heat absorbed on liberated by the process; examples follow. The subject can be considered only very briefly here; for further information see some good modern textbook on chemistry. In the following equations, which are merely the records of many experiments, each symbol stands for a chemical element thus: C = carbon. O = oxygen. Cl = chlorine. Now a chemical equation is:

(84) $$C + O_2 = CO_2$$

which means that 1 atom of carbon, a solid, will combine with

2 atoms of oxygen, a gas, to form one molecule of carbon dioxide gas. A corresponding thermochemical equation is:

(85) 1 *lb.* C + $2\frac{2}{3}$ *lb.* O = $3\frac{2}{3}$ *lb.* CO_2 + 14,650 *B.t.u.*

which means that 1 lb. of carbon will combine with $2\frac{2}{3}$ lb. of oxygen gas and form $3\frac{2}{3}$ lb. of carbon dioxide gas and furthermore that during this process 14,650 B.t.u. of heat energy will be liberated. If 2 lb. of carbon combined with $5\frac{1}{3}$ lb. of oxygen the result would be $7\frac{1}{3}$ lb. of carbon dioxide gas and the liberation of 29,300 B.t.u., and so on. The chemistry books show that an atom of oxygen weighs $1\frac{1}{3}$ times as much as an atom of carbon. This means that (since two atoms of oxygen will combine with one atom of carbon) the weight of oxygen necessary in For. (85) will be: $2\times1\frac{1}{3}=2\frac{2}{3}$ times the weight of carbon required. Note that the weight of the resulting substance "$3\frac{2}{3}$ lb. of CO_2" is the sum of the weights of the two original substances. The energy, obviously, has no weight. Fors. (84) and (85) are very important to the steam engineer since they show the underlying reaction for the chemical process of the combustion or burning of fuels. Combustion is further discussed in Div. 14, which see.

Examples of other chemical and thermochemical formulas are:

(86) $$2H_2O = 2H_2 + O_2$$

which means that 2 molecules of water (H_2O), each composed of 2 atoms of hydrogen and 1 atom of oxygen can be decomposed into 4 atoms of hydrogen, a gas, and 2 atoms of oxygen, a gas. A corresponding thermochemical equation is:

(87) 9 *lb.* H_2O = 1 *lb.* H + 8 *lb.* O − 62,100 *B.t.u.*

which means that 9 lb. of water when chemically decomposed will furnish 1 lb. of hydrogen gas, 8 lb. of oxygen gas and, in addition, that 62,100 B.t.u. of energy must be supplied to effect the decomposition. The minus sign (−) preceding the "62,100" means that this amount of heat energy must be added. A plus sign (+) in the same position means that energy will be liberated during the reaction. That is:

(88) $$2H_2 + O_2 = 2H_2O$$

or stating the corresponding thermochemical equation:

(89) 1 *lb.* H + 8 *lb.* O = 9 *lb.* H_2O + 62,100 *B.t.u.*

which means that if 1 lb. of hydrogen and 8 lb. of oxygen are combined to form 9 lb. of water, 62,100 B.t.u. will be liberated by the reaction. Note that For. (89) is the reverse of For. (87).

Note.—The Rate At Which A Given Chemical Process Is Allowed To Proceed Has No Influence On The Total Amount Of Heat Absorbed Or Liberated Thereby.—Thus, a piece of iron may be permitted to "burn" slowly by rusting away in many months by combining with the oxygen of the air. Or instead it may be permitted to burn away very rapidly—in a fraction of a minute—in pure oxygen gas. But in each case the total amount of heat liberated by the combination of the iron with the oxygen will be the same.

159. "Expansion" Is An Effect Of Increased Molecular Motion in a body of matter. (See Div. 7 for extended discussion.) When the temperature of a body is increased, it expands or increases in size, for the following reason: The molecules of a substance (Sec. 46) are not in actual contact. They are in motion, constantly *vibrating*—hitting one another and rebounding. When their vibratory motion is increased—when the temperature increases—they bounce further away from one another. Thus, there is a tendency to increase the average distance between the molecules. The cumulative effect is an expansion of the whole mass of the substance which they form. But addition of heat is the real cause of the phenomena, since molecular vibration (Sec. 52) is heat. However, addition of heat does not always (Sec. 54 and 187) cause a temperature increase and expansion.

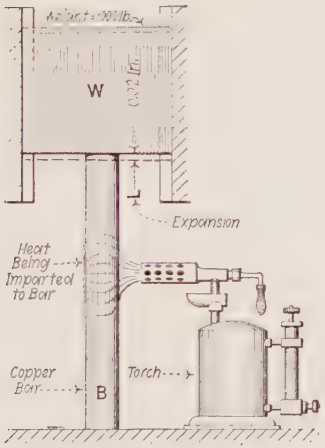


Fig. 147.—Work done by expansion.

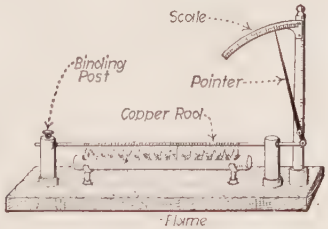


Fig. 148.—Addition of heat expands metals.

Example.—A bar of copper (*B*, Figs. 147 and 148) is longer when hot than when cold.

160. "Contraction" Is An Effect Of Decreased Molecular Motion In A Body Of Matter.—It is the reverse (Sec. 159) of

expansion. Contraction is manifested by a decrease in the size of the body. When the temperature of a body decreases it contracts. The decrease of temperature of a substance consists, essentially, in a diminishment of the vibration of the molecules of the substance. As the vibratory motion of the molecules diminishes. the average distance between them (Sec.

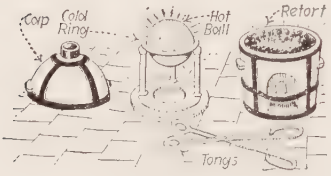


Fig. 149.—The ball will pass through the ring when the ball is cold but will not pass through when it is hot.

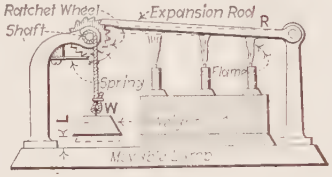


Fig. 150.—Raising a weight by heating and cooling a rod.

52) likewise diminishes. The cumulative effect is a contraction of the entire body of matter which the molecules form.

Examples.—See Fig. 149. Also, a steel collar may be bored to a slightly smaller internal diameter than the outside diameter of a steel shaft. Thus it will be impossible to slip the collar over the shaft when both are at normal temperature. But the collar may be heated. The accompanying expansion will then enlarge its bore until it can be readily slipped over the shaft. If it is then permitted to cool to the temperature

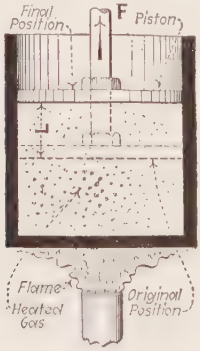


Fig. 151.—Work done by expansion of gas.

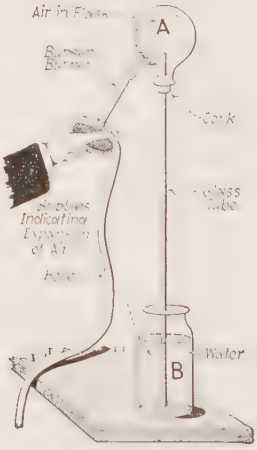


Fig. 152.—Addition of heat causes the air to expand and thus increases its volume.

of the shaft, the collar will gradually contract and will finally grip the shaft so tightly as to be immovable.

Note.—External Work May Be Performed, Through The Expansion And Contraction Of Materials, By Direct Applications Of Heat.—A copper bar (Fig. 147) is heated by the flame of a blow-torch. The bar is thereby expanded and lifts a block, of **W** lb. weight, a distance of **L** in. The external work performed by the applied heat, in lifting the block, may, therefore, be expressed as **WL** in.-lb. $= 1{,}000 \times 0.02 = 20$ *in.-lb.* By alternately heating and cooling the rod *R* (Fig. 150) the ratchet-wheel could be rotated. External work in raising the weight **W,** might thus be performed by the heat energy transferred from the flame to the bar.

Applying heat to a confined gas (Fig. 151) increases the volume of the gas. The gas expands and raises the piston. Thus the heat energy which is transferred from the applied flame is, through the expansion of the gas transmitted into external mechanical work. In Fig. 152, the addition of heat to the air in *A* expands the air, as is shown by the bubbles coming out of the water in *B*, thus external work is done in forcing out the air globules against the force of atmospheric pressure.

161. "Melting" Or "Fusion" Is The Transition Of A Substance From The Solid To The Liquid State. (Fig. 153.) There is, for practically every solid, a certain temperature at which that solid will melt. This temperature is called the *melting-point* or the *fusing-point* of the substance. See Table 285. Furthermore, heat (positive disgregation heat, Sec. 103) is always required to effect the change from solid to liquid form. Thus, melting is an effect of heat addition. This subject is discussed fully in Div. 9.

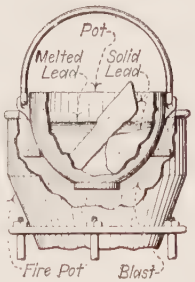


Fig. 153.—Melting lead.

Note.—"Solidification" Is The Opposite Of "Melting." It is the transition of a substance from the liquid to the solid state. Heat (negative disgregation heat) must be given up by it when a body solidifies. Hence solidification is an effect of heat abstraction.

162. "Vaporization" Is The Transition Of A Substance From The Liquid State To The Vapor Form Of The Gaseous State (Figs. 154 and 155). In general, there is a certain temperature (depending on the pressure on the liquid) for each substance at which that substance vaporizes. This temperature is commonly called the *point of vaporization* or *boiling*

point of the particular substance. Furthermore, heat (positive disgregation heat, Sec. 104) must always be added to it to change a substance from the liquid to the gaseous state. Hence, vaporization is an effect of heat. This subject is fully discussed in Div. 10.

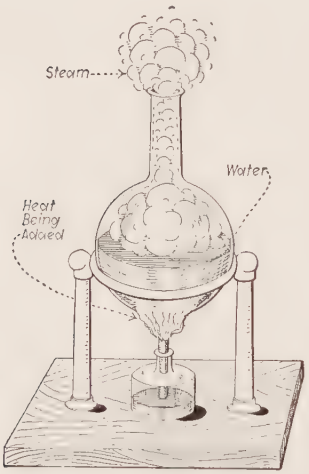


Fig. 154.—Vaporization is the transition from a liquid to a gaseous condition.

Note.—"Liquefaction" Or "Condensation" Is The Opposite Of Vaporization.—It is the transition of a substance from the vapor form of the gaseous state to the liquid state. (In general parlance "condensation" means the reduction of a vapor or gas to the liquid or solid state or of a liquid to a solid or semi-solid state. But in technical usage the term is usually now employed to imply only "the reduction of a vapor to the liquid state") Heat—negative disgregation heat—must be given up by it when a vapor liquefies. Hence, liquefaction is an effect of heat abstraction.

Note.—Melting And Vaporization Are Called Constant-temperature Processes because the heat required to effect them is expended in disgregation work (Sec. 98) and not in vibration work (Sec. 97) which would raise the temperature.

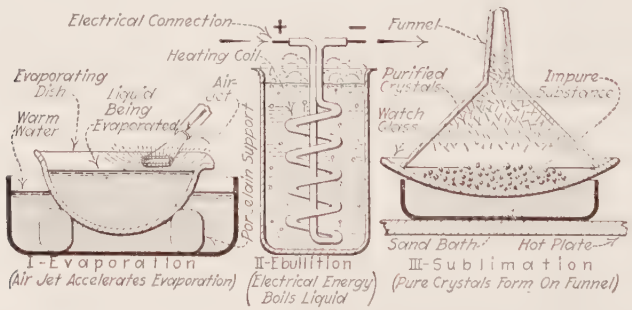


Fig. 155.—Laboratory methods of vaporization and sublimation.

When a block of ice melts to water, the temperature of the resulting water will (Sec. 96) be that of the original block of ice. A great quantity of heat—positive disgregation heat— has, nevertheless, been absorbed in this process of fusion. Conversely, when a liquid substance solidifies, negative disgregation heat is given up by it.

Water may be converted to steam (Fig. 156) without a change of temperature (Sec. 96). Or steam may be condensed to water (Fig. 157) (Sec. 329) without a change of temperature. In the first instance, however, the process can be consummated only by addition of a relatively-great quantity of "positive" disgregation heat and in the second instance only by a corresponding subtraction of "negative" disgregation heat.

FIG. 156.—Change from liquid to gas with temperature constant but with addition of heat. This process may be reversed.

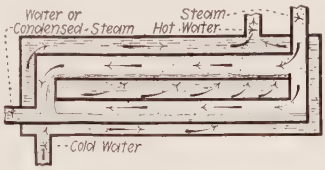


FIG. 157.—The condenser. The heat added to water in the boilers to convert it to steam is given up in the condenser to the cooling water. Thereby, the steam is reconverted into water.

163. Sublimation Is The Direct Transition Of A Substance Which Is In The Solid State To Its Vapor Form Of The Gaseous State, without its, apparently, passing through the liquid state. All solid substances sublime (theoretically at least) at any temperature. The process is somewhat similar to, but not the same as, vaporization; see explanation below. In general, sublimation is a very much slower process than is vaporization. Obviously, sublimation can occur only at temperatures below the freezing point—or melting point. Thus the molecules of a solid substance are found in the vaporous condition above the surface of a solid as well as above that of a liquid. Sublimation is of minor practical importance in power-plant work but is widely used in the chemical industry as a method of purification.

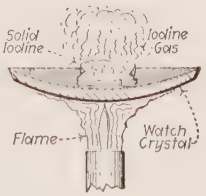


FIG. 158.—Some solids may change to gas without becoming liquid.

EXAMPLES.—SNOW AND ICE WILL SUBLIME even though the temperature of the surrounding air is considerably below the freezing point—so low that the snow or ice can not melt. Damp clothing, which have been hung on a line out-of-doors and then frozen, will become dry in a freezing

temperature. If a piece of solid iodine (Fig. 158) is placed on a watch crystal, and heat is applied, the iodine will sublime directly into a vapor. It will not, apparently, undergo a preliminary liquefaction. The odor of camphor will, due to the sublimation of the camphor, be quickly recognized, some distance away, if a quantity of camphor gum be exposed in a current of air. In general, odors of all sorts, from solid bodies, are evidences of sublimation.

Explanation Of Sublimation.—A molecule which is very near the surface of a solid body may bounce entirely out of it (Fig. 287) without colliding with others. Since such an escaping molecule is already moving at an extremely high velocity, it continues in its now unobstructed path. Soon, it flies so far away from the body that the remaining molecules (in the solid substance) exert no attractive force on the insurgent. The molecule, now being free of the restraints which were imposed on it in the solid, becomes a gas or vapor molecule.

164. The "Heat Of Sublimation," sometimes also called *the latent heat of sublimation*, is the amount of heat—usually expressed in British thermal units—required to sublime, or to convert into a vapor, a unit weight—usually 1 lb.—of the solid. The heat of sublimation can be conveniently calculated as the difference between the heat content of the solid and that of the vapor. At the *triple point* for the substance (which is that temperature and pressure at which a substance can exist in either the solid, the liquid, or the gaseous state) it is true that:

(90) *Heat of sublimation* = (*Latent heat of fusion*) + (*Latent heat of vaporization*)

The above For. (90) will also hold quite closely for any temperature of the solid near the triple-point temperature. More accurately, for any given temperature of the solid, the heat of sublimation is (very closely) the same as the net amount of heat that is necessary to: (1) *Warm the solid to its melting point.* (2) *Melt the solid.* (3) *Vaporize the resulting liquid.* (4) *Decrease the temperature of the resulting vapor from that of the vaporization to the given temperature* at a constant quality of 100 per cent. This heat to *decrease* the temperature is a substraction—not an addition.

Example.—At 32° F., the latent heat of vaporization for water is 1,073.4 B.t.u. per lb., as is shown by steam Table 394. The latent heat of fusion of ice, from Table 291 is 143.33. What is the heat of sublimation of ice at this temperature? Solution.—Substituting in For. (90): *Heat of sublimation* = (*Latent heat of fusion*) + (*Latent heat of vaporization*) = 143.3 + 1,073.4 = 1,216.7 *B.t.u. per lb.*

165. Viscosity Is The Internal Friction Of Liquid, Semi-liquid, Or Plastic Substances.—It occurs as the molecules flow by one another. Every substance possesses this internal friction in some degree. Practically all solid substances, acquire, when heated, a tendency to flow. That is, their viscosities decrease as their temperatures increase; they become liquid, semi-liquid, or more or less plastic. The viscosities increase as the temperatures diminish. Thus a change of viscosity is an effect of heat.

Note.—The Flowing Tendency—The Difference In Viscosity—Of Substances Is, Obviously, The Chief Difference, Between Solids And Fluids. Is is commonly assumed that: *A fluid is any substance that exhibits a definite flow to ordinary observation.* By this definition, both the molten iron gushing freely from the tap-hole of a foundry cupola, and the stream of thick slag rolling ponderously and sluggishly from the slag-hole, are fluids. Likewise, this definition of a fluid includes all gaseous substances. However, the definition eliminates from consideration all apparently plastic substances, as masses of beeswax, moist putty, building mortar, and the like.

Examples.—A wax candle (Fig. 159), whether held horizontally or vertically, will ultimately bend under its own weight in a warm room; it is highly viscous. A mass of relatively cold pitch, apparently hard, is likewise susceptible to changes of shape, due to its own weight. Bodies of other viscous substances such as molasses, honey, tar, oil and similar substances, undergo changes of shape somewhat in the manner of true liquids, as water, though less rapidly. A mass of solid lead, at normal temperature, will flow when subjected to pressure.

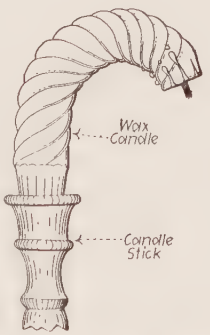


Fig. 159.—A wax candle becomes soft in a warm room.

166. The Viscosity Of A Substance Varies With Its Temperature.—The higher the temperature the less the viscosity. The wax of a candle (Fig. 159) is, normally, quite viscous. It may, however, be readily heated to a temperature that will vastly diminish its viscosity. Under a very high temperature the wax will become extremely thin and fluid. The viscosity of lubricating oils likewise varies, though to a far less extent, as the temperature varies. The quantitative effect of temperature on viscosity varies with the different materials.

Note.—Mobility Is, In A Sense, The Opposite Of Viscosity.—A very thin liquid, that pours readily and splashes freely, is said to possess *mobility*.

167. The Specific Viscosity Of A Liquid is the ratio of the time consumed by a certain volume of the liquid (Fig. 160), at 60° F., in flowing through an orifice, to the time consumed by an equal volume of distilled water in flowing, under the

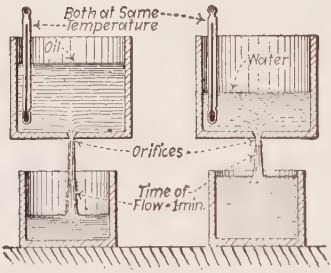


Fig. 160.—Showing difference in viscosity of oil and water.

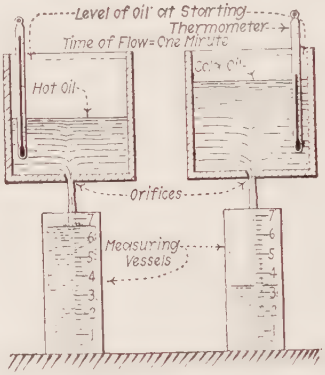


Fig. 161.—Showing difference in viscosity of hot and cold material.

same conditions, through an orifice of the same dimensions. The quantity of the liquid is usually taken as 50 c.c. (cubic centimeters).

Note.—The Temperature In Viscosity Tests is often taken at other than 60° F. It may be 120° F. For many purposes, 212° F. may be a convenient test temperature. When a lubricating oil is intended for an engine cylinder using superheated steam, or for an internal-combustion engine, the test temperature is correspondingly high. It is important that viscosity tests of lubricating oils (Fig. 161) be made at the temperatures under which the oils are to be used.

168. Many Solid Substances Possess The Property Of Absorbing Or Liberating Gaseous Substances.—Temperature—the degree of heat—is often a determining factor in these phenomena. A solids' capacity for absorbing a gas is generally less when the solid is hot than when it is cold. Heat is often liberated by the absorption of a gas by a solid.

Examples.—A fine platinum wire, held in a mixture of hydrogen and oxygen gases will absorb the oxygen very rapidly. The wire will,

spontaneously become heated to incandescense and will finally ignite the surrounding gas; see explanation below. Endeavors have been made to utilize this principle (Figs. 162 and 163) in the making of gas-lighters.

A quantity of wood charcoal (Fig. 164) will absorb a quantity of gas which, normally, may occupy many times the volume of the charcoal. Boxwood charcoal will absorb a volume of ammonia equal to 90 times its own volume. Likewise, it will absorb 35 times its own volume of carbon dioxide.

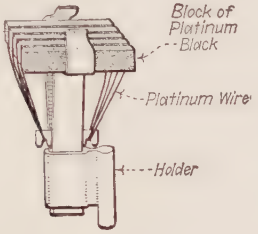


Fig. 162.—A gas lighter. Platinum black glows due to gas absorption. Platinum wire is thereby heated, becomes incandescent and lights gas.

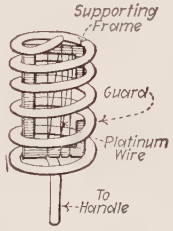


Fig. 163.—A platinum-wire gas igniter.

Explanation.—It is claimed that all solid substances will, at their surfaces, exert an attraction on the molecules of gases with which they are in contact and that this attraction is of such a nature that a more or less thick layer of the gas is condensed on the surface of the solid. Thus, solids such as charcoal, which because of its porous structure exhibits a large external surface, will "absorb" more gas than structurally dense solids. The attractions of the molecules of different solids and different gases are not the same. Freshly made dogwood charcoal (used in making the best gunpowder), when pulverized immediately after its preparation, often takes fire spontaneously on account of the heat liberation which accompanies the condensation on its surfaces of oxygen from the air. Likewise, when platinum in a finely divided state known as *platinum black* (Fig. 162) is placed in a mixture of oxygen and hydrogen, the oxygen rapidly condenses on its surface and gives up its latent heat of vaporization (Sec. 322). This raises the temperature of the surrounding particles of gas to the point where they combine slowly. This slow burning, however, gives off much heat to the surrounding particles. Hence, the temperature of the gaseous mixture quickly reaches a value which explodes the mixture.

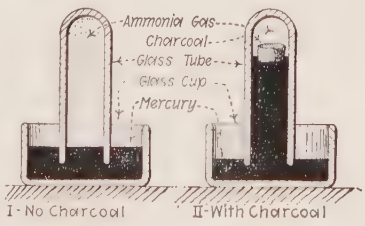


Fig. 164.—Illustrating absorption of a gas by a solid.

Note.—The Gas-absorptive Property Of Charcoal Renders It Valuable For Counteracting The Noxious Effects Of Gases Resulting From Animal And Vegetable Decay.—It is commonly used for clarifying the air in the holds of sea-going vessels, and in tunnels. Charcoal made from nut shells is extensively used in gas masks for absorbing poisonous gases.

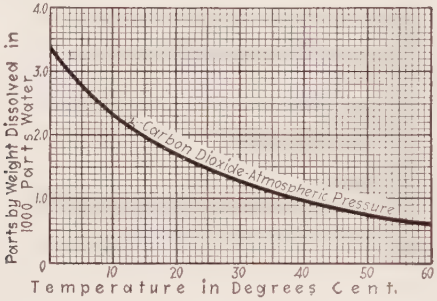


Fig. 165.—Showing variation of solubility of carbon dioxide in water with variation of temperatures. (Plotted from Smithsonian Tables.)

169. Liquid Substances Possess The Property Of Absorbing Or Liberating Gaseous Substances.—A liquid will generally absorb (Fig. 165) more gas when it is cool than when it is hot.

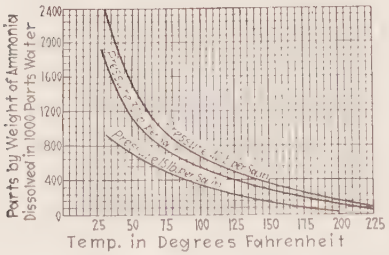


Fig. 166.—Showing effect of heat on the amount of ammonia gas held in a water solution. (Plotted from values in Mark's "Mechanical Engineers' Handbook.")

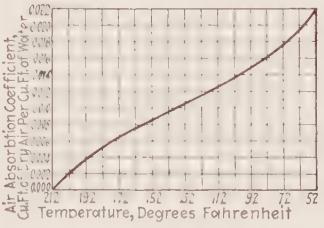


Fig. 167.—Air absorption of water at various temperatures.

Examples.—Ammonia gas is readily absorbed (Fig. 166) by cool water. The resultant mixture is known, commercially, as aqua ammonia (ammonia water). Boiling will expel the gas from a mass of aqua ammonia. These principles are utilized (Sec. 637) in the operation of absorption refrigerating systems. Water (Fig. 167) is always impregnated, more or less, with air. Slow heating of a quantity of cool water (Fig. 168) causes

small bubbles to appear. These are due to release of air from the liquid. Fish breath air from the water in which they live.

Note.—Pre-expulsion Of Oxygen And Other Gases From The Boiler Feed Water In Power Plants Is Often Necessary.—Such gases might otherwise become distilled from the water after it enters the boilers. Thus they would be rendered free to form corrosive acids within the boilers. By preheating the feed-water (Fig. 169) much deleterious gas may be driven off.

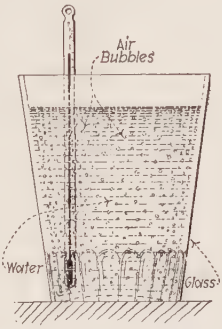


Fig. 168.—If a glass of cold water is placed in the sun's rays on a hot day and allowed to stand until warm, small air bubbles will cling to surface of glass. Air was in solution.

170. Many Solids Are Soluble In Liquids.—If a small permanganate-of-potash crystal is dropped into a vessel of water, the adjacent water will, immediately, become colored. By degrees, all of the water will become colored. The crystal has *dissolved* in the water. Similarly, if sugar crystals be placed in a tumbler of water, they will dissolve therein. The water will become sweet. Heat is usually liberated or absorbed while a solid goes into solution in a liquid. Hence, *solution is an effect of heat.*

Examples.—Water is a solvent for a greater number of different solids than any other known liquid. Alcohol is a solvent for some solids for

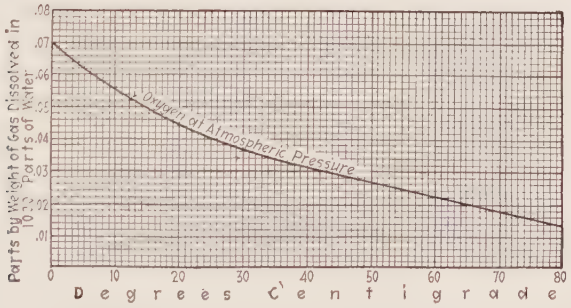


Fig. 169.—Showing effect of heat on amount of oxygen held in a water solution.

which water is not. Thus, resin and shellac dissolve readily in alcohol but not at all in water. Most greases are soluble in benzine. Beeswax is soluble only in turpentine. Sulphur is soluble in carbon bisulphide.

171. The Quantity Of A Solid Which A Given Liquid Will Dissolve Is Determined By The Nature Of The Substances And Their Temperatures (Fig. 170). Water will dissolve

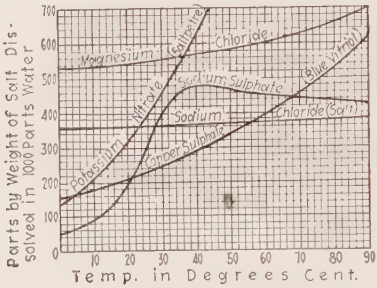


Fig. 170.—Showing the effect of heat on the solubility of various salts in water. (From Smithsonian Physical Table.)

Fig. 171.—A hot liquid usually dissolves more of a solid than will a cold one.

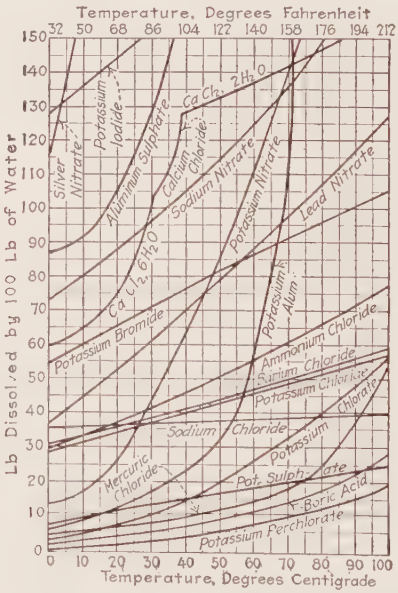


Fig. 172.—Graphs showing variation with temperature of the solubility of various substances in water. (Alex Smith, "College Chemistry.")

about three times as much table salt as will alcohol. When a liquid, at a certain temperature, has dissolved all of a certain solid which it will absorb, it will, generally, dissolve more

(although sometimes less) of the solid if the temperature of the liquid is increased (Fig. 171). The effect of variations in temperature on the solubility of various solids in water is shown graphically in Fig. 172. It will be noted that common salt (sodium chloride) has an almost constant solubility. The rate of dissolving of salt is, of course, much greater at a higher temperature. Also, the rate of dissolution (rapidity of dissolving) may usually be increased considerably by raising the temperature.

Note.—A Saturated Solution exists when a liquid has dissolved all of a substance which it will absorb from the solid form at that temperature. The solution is then said to be *saturated.*

172. Dissolving Solids In Liquids Often Causes A Temperature Change.—When there is a temperature change there is usually a volume change also. That is, the solution will occupy a different volume from the sum of the volumes of the solid and original liquid. Sometimes heat is absorbed; sometimes it is given off. The volume of the solution may be greater or less than the sum of the volumes of the solid and original liquid. Some substances dissolve or unite with water with the liberation of much heat. When this occurs, a well-defined chemical reaction has usually occurred.

173. The Vapor Issuing From A Hot Solution Is, Generally, Free From Solid Matter.—The solids are left in solution in the containing vessel. Hence, if all of the liquid content of a solution is boiled away, the total solid portion may thereby be recovered. This phenomena is of considerable importance in power-plant operation. The solids which are carried in solution in the boiler feed water are deposited on the interior of the boiler shell as the water is evaporated and passes away as steam. Similar solid-matter deposits occur in condensers. A somewhat similar phenomena is distillation, (Sec. 345).

Note.—Some Solids Are Held More Readily In Cold-water Solutions Than Hot-water Solutions.—This is an additional cause of solid-matter deposits in steam-generating vessels. Thus, natural waters frequently contain calcium bicarbonate which, when heated to about 212° F., decomposes giving calcium carbonate, a relatively insoluble substance. The calcium carbonate collects on the interior surfaces of the vessel forming a spongy solid mass. Another salt, calcium sulphate, comes less soluble when heated to about 300° F. than when cold. If,

due to evaporation, a solution becomes concentrated with calcium sulphate, this salt will settle as a hard, porcelain-like coating inside the boiler—it is very difficult to remove and offers great resistance to the passage of heat through it.

174. "Scale" Is The Hard Substance Which Forms On The Interior Surfaces Of Boilers And Power-plant Auxiliaries Which Carry Hot Water.—Scale is formed (Sec. 345) by precipitation and hardening of the solids (salts) carried in the cold, or relatively cold, feed water. Scale is usually formed from "hard" water. *Hard water* may be defined as water which contains in solution mineral compounds that curdle or precipitate soap when soap is added to the water.

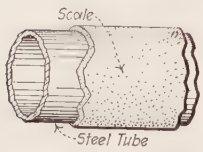


FIG. 173.—Section of tube from fire-tube boiler showing deposit of scale around it—due to heat.

Important among the many scale-forming solids found in boiler-feed and condensing waters are *calcium sulphate, calcium carbonate, magnesium sulphate, and magnesium carbonate.*

NOTE.—WHEN SUCCESSIVE INCREMENTS OF THE ABOVE SPECIFIED SOLIDS ARE PRECIPITATED in a containing vessel, as a steam boiler, they become cemented (Fig. 173), by absorption of heat from the heating surfaces, into a solid and more or less hard coating of scale. Such scale clings tenaciously to the metal surfaces. Since scale is a very poor conductor of heat, it affects economy very adversely. This subject is further treated in the author's STEAM BOILERS.

175. Heat Energy May Be Transformed Directly Into Electrical Energy.—When two dissimilar metals, as antimony and bismuth, are placed in contact, an electromotive force develops at their junction. If the two metals be connected to form a closed circuit (all parts of the circuit being at the same temperature), electromotive forces will also be produced at the other junctions of dissimilar metals and the sum of all electromotive forces in the circuit will be zero—hence no current will flow in the circuit. But if one junction of the dissimilar metals is heated, as in Fig. 174, a decidedly larger electromotive force will be developed at that junction. A current will then flow in the circuit.

NOTE.—EXCEPT IN THE CONSTRUCTION OF PYROMETERS (FIG. 175) THERE ARE FEW PRACTICAL APPLICATIONS OF THE ELECTRICAL EFFECT

Of Heat.—The current flowing (Fig. 175) is an indication of the difference in temperature between the hot joint, *H*, and the cold joint, *C*. If a sufficient number of thermo-couple cells (Fig. 174) be connected in series,

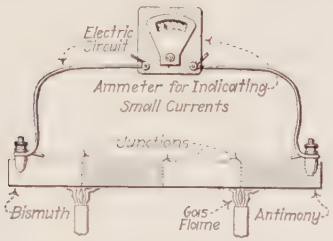


Fig. 174.—The thermopile.

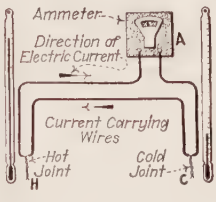


Fig. 175.—Principle of the thermo-couple electric pyrometer for measuring high temperatures.

the resulting battery will furnish enough energy to heat, to incandescence, the filament of a small electric lamp.

176. Light May Be Regarded As An Effect Of Heat.—It is the visible criterion of radiant energy (Sec. 31). Hence, since radiant energy is emitted only by hot bodies, heat may be considered as a fundamental source of light. Light waves can be shown to also carry radiant heat. This may be shown by causing the light to impinge upon surfaces which possess certain qualities. A black surface is the best absorber of light. A black surface is always found to absorb heat as it absorbs light.

177. "Radiant Energy" Is A Vibratory Motion In The Æther.—When an object is heated, the molecules which compose it are made to vibrate more rapidly. These particles, being in contact with the æther, set it in motion. Thus, the vibrations are transmitted away from the object as radiant energy. Heat which is transmitted by radiation is radiant heat. See Sec. 138 for a further discussion of this subject.

Examples.—The heat which reaches the earth from the sun is radiant heat. A hot stove will radiate heat. The radiant heat from the sun will warm the interior of a greenhouse, even when the outside air is cold. This proves that the sun's radiant heat is transmitted through the æther rather than through the air. Radiant energy (light or heat) will cause a *radiometer* (Fig. 176) to rotate.

178. Radiant Energy May Be Said To Be Visible Or Invisible according to the length of its wave in the æther. Waves in the æther may be thought of as similar to the waves which travel along the surface of a pool of quiet water when a pebble is dropped into it. The *wave length* (see Table 19) is the distance from the crest of one wave to the crest of the next. Æther waves have different wave lengths. Waves of lengths from about $\frac{1}{64,000}$ in. to $\frac{1}{32,000}$ in. act upon the nerves of the eye and thereby produce the sensation of sight.

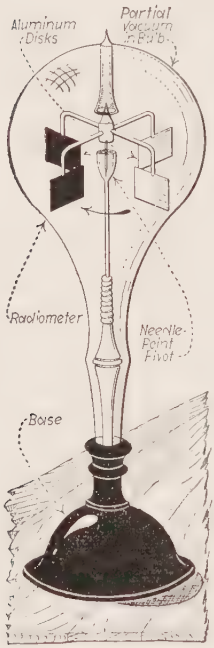


FIG. 176.—Light from the sun or even from a candle will cause the radiometer to rotate. The aluminum vanes are coated on one side with lamp black which is a good absorber of radiant energy. If only a slight vacuum exists in the bulb, the vanes will so rotate that the blackened sides move toward the light. The explanation of this action is: The black faces absorb radiant energy and are heated thereby. The air immediately adjacent to these black faces is also heated. The heated air rises by convection and thus causes a slightly smaller pressure on the black face of a vane than on its bright face. This slight difference of pressure causes rotation. But if the bulb is very well exhausted, its rotation will be such that the blackened faces move away from the light. The explanation of this action is too lengthy to be given here; the reader is referred to a good textbook on physics.

Such are called *light waves*. *Heat waves* are *longer* than light waves varying in length from about $\frac{1}{32,000}$ in. to $\frac{1}{7,000}$ in.

NOTE.—WAVES SHORTER THAN $\frac{1}{64,000}$ IN. DO NOT AFFECT THE EYE-NERVES, hence they are invisible. But some of these short waves will cause certain chemical actions—they will cause reactions in the coating on a photographic plate. These invisible short waves are called ultra-violet waves.

NOTE.—LIGHT-, HEAT- AND ELECTRIC-WAVES ARE ALL ÆTHER WAVES AND ALL TRAVEL AT THE SAME SPEED, which is about 186,000 mi. per sec. But they differ in wave length, that is, in frequency. Electrical, or wireless-telegraph and telephone waves are much longer (they may be several miles long) than heat-waves. However, they possess the same general characteristics. Herein is evidenced the close connection between—or possibly the fundamental identity of—light, heat, and electricity. See the Author's PRACTICAL ELECTRIC ILLUMINATION for a further and detailed explanation of the transmission of radiant energy through the æther.

179. Table Showing The Wave Lengths Of Radiant Energy.—Waves shorter, even than those here listed are radiated in the form of X- and gamma rays. (From the SMITHSONIAN TABLES.)

Visibility	Kind of wave	Wave length		Number of waves per inch	Frequency in cycles per second
		Centimeters	Inches		
Too short to be visible	Shortest ultra-violet	0.000,006	0.000,002	420,000.	5,900,000,000,000,000
Visible	Shortest visible (violet)	0.000,036	0.000,014	69,000.	840,000,000,000,000
	Violet, longest	0.000,045	0.000,017	56,000.	690,000,000,000,000
	Blue, shortest	0.000,045	0.000,017	56,000.	690,000,000,000,000
	Blue, longest	0.000,049	0.000,019	52,000.	620,000,000,000,000
	Green, shortest	0.000,049	0.000,019	52,000.	620,000,000,000,000
	Green, longest	0.000,055	0.000,021	46,000.	560,000,000,000,000
	Yellow, shortest	0.000,055	0.000,021	46,000.	560,000,000,000,000
	Yellow, longest	0.000,059	0.000,023	43,000.	510,000.000,000,000
	Orange, shortest	0.000,059	0.000,023	43,000.	510,000,000,000,000
	Orange, longest	0.000,065	0.000,026	39,000.	450,000,000,000,000
	Red, shortest	0.000,065	0.000,026	39,000.	450,000,000,000,000
	Red, longest visible	0.000,077	0.000,030	33,000.	390,000,000,000,000
To long to be visible	Infra-red (heat) longest	0.03	0.012	85.	990,000,000,000
	Electric (wireless), shortest	0.2	0.079	13.	150,000,000,000
	Electric (wireless), longest	1,000,000.	390,000.	0.000,002	30,000

180. Different Wave Lengths Cause Different Color Sensations.—See Table 179. When the vibrations of the particles of a heated substance become so frequent that 400,000,000,000,000 waves are transmitted per second (wave length = about $\frac{1}{34,000}$ in.) the color sensation of red results. If the substance is heated to higher temperatures, its molecules vibrate still more rapidly as its temperature increases. Its colors then successively are: (1) *Red.* (2) *Blood Red.* (3) *Dark Cherry.* (4) *Medium Cherry.* (5) *Cherry or Full Red.* (6) *Bright Red.* (7) *Salmon.* (8) *Orange.* (9) *Lemon.* (10) *Light yellow.* (11) *Straw.* (12) *Light straw.* (13) *White.* Each color corresponds to a certain temperature as shown in Table 63. These colors are utilized as temperature indication in tempering steel.

Note.—When A Beam Of Sun Light Is Broken Up Into Its Different Component Colors, By The Interposition Of A Glass Prism in its path, the colors in the resulting *spectrum* appear (Table 179), in a descending progression as to wave-length, as *red, orange, yellow, green, blue, indigo,* and *violet.* This shows that the light emitted by the sun is due to waves of all visible lengths. We know, from common observation, that heat waves are also radiated from the sun. It has also been shown by careful experiments that all "light" waves are, at the same time, radiant "heat" waves—that is, that all light waves will heat a substance in which they are absorbed.

181. The Specific Purpose Of All Forms Of Illuminating Devices, Or Lamps, Is To Disseminate Æther Waves.—In the design of lamps it is particularly sought to secure a maximum of lighting effect with a minimum accompaniment of heat. Perfection in the operation of a lamp would be attained if it emitted light waves only without heat waves. Since, however, light waves are at the same time heat waves, the desired result has never been realized. Issuance of light with practically no liberation of heat may be observed in the physiological processes of the glowworm and firefly, and in certain other phosphorescent phenomena. In these, the rate at which the heat is liberated is so slow that the temperature, of the so-called "heatless?" light sources, remain low. But artificial duplication of these natural processes, upon a commercially practicable scale now appears to be unattainable.

Note.—An Ordinary Kerosene Lamp, gives off as light (luminous radiant energy) only about 0.04 per cent. of the available energy in the oil. The remaining energy is dissipated in the surrounding air as non-luminous, radiant energy and in heating the air by conduction. Carbon-filament electric lamps give out, as light, only about 0.4 per cent. of the electrical energy which they consume. Gas-filled Mazda lamps give out about 3.0 per cent. Some highly efficient arc-lamps give out as light 7.0 per cent. of the total electrical energy which they consume; the remainder, 93 per cent., is given out as heat which warms the surrounding atmosphere and objects.

Note.—The Efficiency Of A Lamp Ordinarily Increases As The Temperature Of The Illuminating Element Increases.—The filament-temperature in a gas-filled electric lamp is much higher than in any other type of electric filament lamp. This accounts for its relatively high efficiency.

Note.—Momentary Reductions Of The Voltage Which Operates An Electric Lamp Results In Corresponding Momentary Diminishments Of Its Lighting Effect.—A small voltage-diminishment produces a considerable decrease in lighting effect. Such fluctuations of emitted light are due directly to the very slight decreases in filament-temperature which attend the momentary drop of voltage. On the other hand if the temperature of the filament is kept higher than that for which it was designed, the "life" of the lamp will be greatly curtailed. Hence the importance of maintaining the filaments at as high—but at no higher—a working temperature as is consistent with considerations of durability is evident. This subject is discussed fully in the author's Practical Electrical Illumination and American Electricians' Handbook.

182. If The Temperature Of An Electrical Conductor Be Increased, Its Resistance To Current Flow Will Generally Be Increased.—Thus the power available at the receiving end of a transmission line may decrease as the temperature of its conductors increases. This principle is utilized in certain temperature-measuring instruments. See Sec. 669 for a description of a resistance pyrometer.

Note.—The Attractive Force Of A Permanent Magnet is decreased by applications of heat. Thus if a horseshoe magnet is heated its magnetic strength is decreased. This effect of heat can be verified by the following simple experiment: Take an ordinary darning needle and stroke it over a permanent magnet a few times. The darning needle will then attract other needles; that is, it has been magnetized. If the needle is then heated in a flame to a red heat and allowed to cool, it will be found that it does not attract other needles anymore; hence it has lost its magnetism.

183. Table Showing Strengths Of Metals At Various Temperatures.—The strength of the metal at 70° F. is taken as the basis for comparison. These data are plotted into the graphs of Figs. 177 and 178.

Metal		Strengths at different temperatures (Fahrenheit)								
		70°	210°	400°	570°	750°	930°	1,100°	1,300°	1,475°
Bronze	Lb. per sq. in.	50,000	50,500	47,000	28,500	13,000	9,000			
	Per cent.	100	101	94	57	26	18			
Cast iron	Lb. per sq. in.	15,000	.....	15,000	14,850	13,800	11,400	6,300		
	Per cent.	100	.....	100	99	92	76	42		
Cast steel	Lb. per sq. in.	70,000	76,400	87,600	84,700	67,900	39,900			
	Per cent.	100	109	125	121	97	57			
Copper	Lb. per sq. in.	35,000	33,200	29,800	25,600	20,600	14,700			
	Per cent.	100	95	85	73	59	42			
Structural steel	Lb. per sq. in.	60,000	61,800	79,200	73,200	51,600	29,400	16,800		
	Per cent.	100	103	132	122	86	49	28		
Wrought iron	Lb. per sq. in.	48,000	50,000	53,800	55,800	46,100	36,500	20,200	12,000	7,200
	Per cent.	100	104	112	116	96	76	42	25	15

184. The Strengths Of Metals May And Generally Do Vary With Their Temperatures.—High temperatures (Table 183—Figs. 177 and 178) generally reduce the strengths of metals.

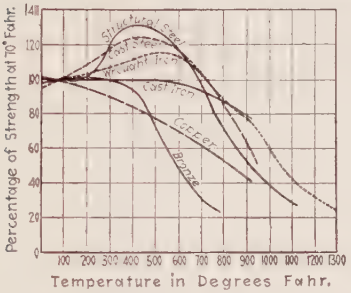


FIG. 177.—Showing percentage variation in strength of different metals with variation in temperature. (Values computed from those of Fig. 178.)

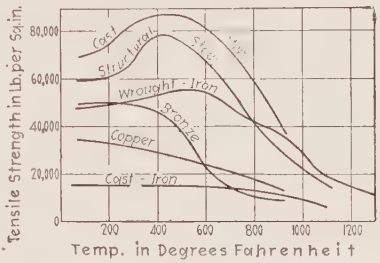


FIG. 178.—Graph showing variation of strengths of metals as temperature rises. (Plotted from values in MACHINERY'S HANDBOOK, p. 300.)

But low temperatures may also produce weakening effects; a freezing temperature (32° F.) renders steel, very brittle. Other metals also become extremely brittle at low temperature.

QUESTIONS ON DIVISION 6

1. What are the three possible effects of adding heat to a substance or abstracting heat from it?

2. What is a *property* of a substance. Name several properties. Can properties be changed?

3. Define a *process*. Give several examples of processes.

4. What is a physical process? Give several examples. In this division, what physical processes are discussed?

5. Explain the difference between a reversible and an irreversible physical process and give examples of each. Into which class do most physical processes fall?

6. What is a chemical process? What four general types of chemical process are there? Explain each and give examples.

7. Explain what heat effects may accompany chemical reactions. Give examples.

8. Define *dissociation*. What is the difference between a dissociation and a decomposition? Give examples to illustrate the difference.

9. What causes a body to expand? Explain.

10. What is *contraction*?

11. How may expansion of materials be utilized for doing work? Describe two examples in full.

12. What is *melting*? *Fusing*?

13. What is the transition of a substance from liquid to vapor called?

14. Does the temperature of a substance change while the substance is in process of melting? While in process of vaporization?

15. Does melting or vaporization of a substance require absorption of additional heat by the substance?

16. Give some examples of the sublimation of solids.

17. Explain what happens when a solid sublimes.

18. What is *viscosity?*

19. How is a solid distinguished from a liquid?

20. What is the effect of temperature upon the viscosity of a substance?

21. How does a liquid manifest *mobility?*

22. What, in general, is *specific viscosity?*

23. At what temperatures are the specific viscosities of substances defined?

24. How does temperature affect the gas-absorptive property of solids?

25. Explain fully how gases are absorbed in solids.

26. Give examples and uses of gas-absorptive solids.

27. State the phenomena by which the gas-absorptive property of liquids may be demonstrated.

28. What liquid is it that will dissolve a greater number of different solids than any others? Name other solvents.

29. Upon what factors does the dissolving capacity of a liquid depend?

30. What effect does the dissolving of a solid in a liquid have on the temperature of the solution. Discuss in full.

31. Do vapors carry solids in solution? What is the special significance of this fact in power-plant operation?

32. How is scale formed in a steam boiler?

33. Describe an apparatus for generating electrical energy directly from heat. How is it used commercially?

34. What is light? What are some of the characteristics of light? What is the cause of light? What is color? What is the relation of color to temperature.

35. Are ordinary lamps efficient in their production of light? What effect do changes of temperature of the illuminating element of an electric lamp, produce in the quality of the light afforded?

36. How does temperature affect the strength of metals?

37. How is the electrical resistance of a substance dependant on its temperature? What commercial use is made of this fact?

DIVISION 7

EXPANSION AND CONTRACTION OF SOLIDS AND LIQUIDS

185. "Addition Of Heat Causes Expansion, Withdrawal Of Heat Causes Contraction" (Fig. 179) is, in general, true for all substances. There are, however, certain exceptions; see Sec. 187. This subject has already been discussed, briefly, in Sec. 159. There it was explained that addition of heat causes an increase in molecular vibration. Hence, expansion results. Withdrawal of heat causes a decrease in molecular vibration. Thereby, contraction ensues. In this division, the subject will be treated in more detail.

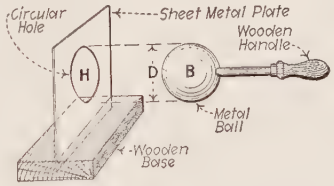


FIG. 179.—Heat expands objects. (When cold, both the hole H and ball B are of the same diameter, then B will just pass through H. But, when B is heated, it will not pass through H.)

186. Expansion And Contraction Of Solids will be considered first. In general, when the temperature of any solid is

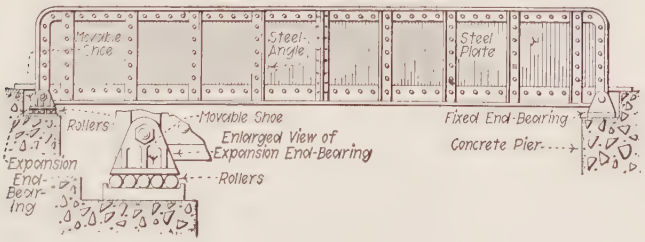


FIG. 180.—Girder bridge with provision for expansion (bridges over 100 ft. long usually have roller bearings; from 50 to 100 ft. span may have friction shoes instead of roller shoe).

increased, it becomes larger. When its temperature is decreased, it becomes smaller. Many examples of these phenomena are familiar to all.

Examples.—Electric wires on pole-lines sag further on a hot day than on a cold day. Railway track-rails expand on hot days, and buckle. This may cause wrecks. Steel bridges have expansion joints (Figs. 180 and 181), so that expansion of the span will not cause damage. Wagon tires are heated to render them sufficiently large to fit over the felloes;

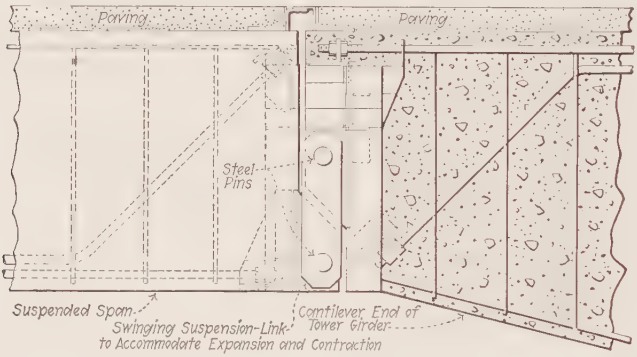


Fig. 181.—Swinging-link expansion joint used in reinforced-concrete viaduct.

in cooling, the tire contracts and renders the whole very rigid. In making machinery, metal collars are, often, expanded by heat and then allowed to shrink firmly onto shafts. Brick power-house chimneys are often made double so that excessive expansion of the inner shell will not affect the outer. A heated journal in a bearing may expand and become siezed.

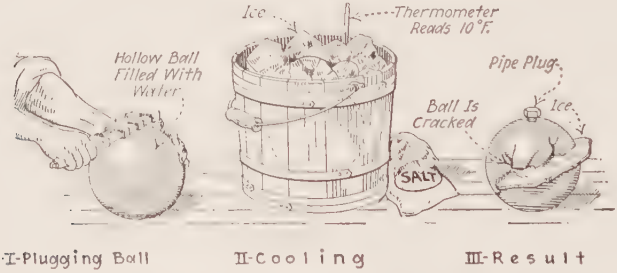


Fig. 182.—Illustrating the effects of freezing in a closed vessel. A hollow cast iron ball filled completely with water and plugged is placed in a pail containing ice and salt. As the water freezes, it *expands* and the force of expansion breaks the ball.

187. Exceptions To The General Rule That Heating Expands Substances And Cooling Contracts Them are these: As water is cooled, it contracts until its temperature has decreased to 39.2° F. (4° C). But as it is cooled further, it

expands. It may solidify into ice. But, as is common knowledge, ice occupies greater volume than the water from which it forms and may, in freezing, break pipes (Fig. 182) and split rocks. See following Sec. 209 for a further discussion. The metals iron, antimony, and bismuth contract on melting and expand on solidifying. The contrary might reasonably be expected since, obviously, melting requires the addition of heat. On the other hand, certain other metals—gold, silver, and copper, for example—expand in melting and contract in solidifying. Hence, these latter metals cannot conveniently be cast but must be stamped.

188. The Amount Of Expansion For The Same Temperature Increase, Is Different in Different Substances.—Likewise the amount of contraction, for the same temperature decrease, is different. These facts have been verified, experimentally, many times. This property is utilized practically in a number of different devices, as explained in the examples below:

EXAMPLE.—Rubber (see Table 192) expands 0.000,042,8 of its length for each degree Fahrenheit temperature increase. Cast brass expands 0.000,010,4 of its length per degree Fahrenheit. Thus, the expansion of the rubber is about four times as great as that of brass. Hard glass, however, expands only 0.000,003, 3 of its length per degree Fahrenheit increase.

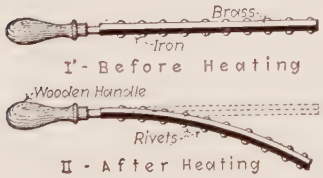


FIG. 183.—The compound bar (cold and heated).

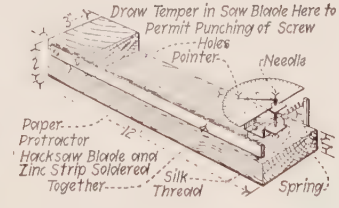


FIG. 184.—Home-made thermometer operating on the compound-bar principle. (L. Pyle in *Popular Mechanics*.)

EXAMPLE.—If two similar strips of metal which expand at different rates are fastened together (Figs. 183 and 184) by riveting or welding, the strains which occur when the *compound bar* is heated will cause the bar to bend, somewhat as shown in the illustration. This principle is applied in various devices and instruments. The bending is due to the fact that the length of one of the component strips increases more for the same temperature rise than does the length of the other.

EXAMPLE.—THERMOSTATIC METAL (Figs. 185, 186 and 187) is made by welding together permanently, through their entire length with the

oxyacetylene flame, two strips of metal which have widely different expansion coefficients. It is used for temperature indication, tempera-

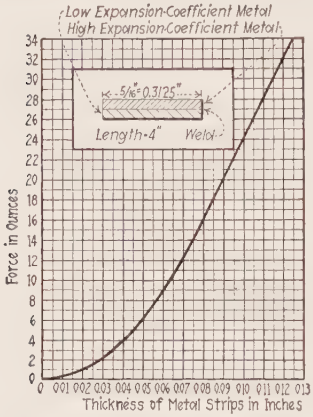


FIG. 185.—Force exerted by a *General Electric Company* thermostatic metal strip for a 100° F. temperature change.

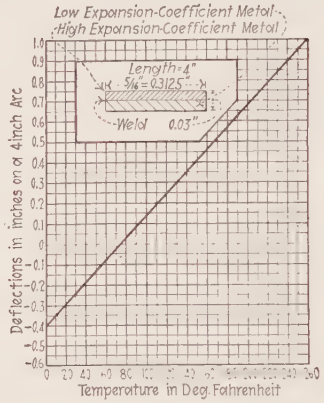


FIG. 186.—Deflection of *General Electric Company* thermostatic-metal strip with the temperature.

ture control, or temperature compensation in: oven thermometers, electric heaters, ice machines, refrigerators, thermostats, automobile ignition control, battery-charging control, electric-signal control, and carburetors.

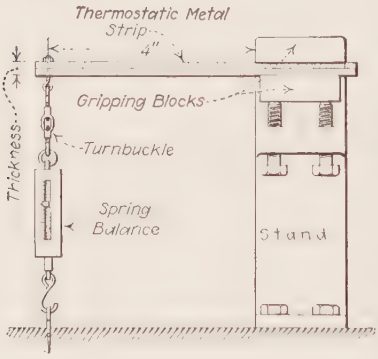


FIG. 187.—Showing probable apparatus employed in testing thermostatic metal strip in determining the values from which Fig. 185 was plotted; the metal strip was probably enclosed in a tube wherein any desired temperature would be provided. The values from which Fig. 186 was plotted were probably obtained by permitting the metal to deflect free—that is, without using the spring balance.

EXAMPLE.—The thermostat (Fig. 188) operates on the compound-bar (Fig. 183) principle. A thermostat may be used for closing the circuit in an electric-signal system, to sound an alarm, if the temperature becomes excessive. Thermostats are also used to regulate the dampers in heating systems. Thereby, they provide automatic heat control. When the room becomes too warm, the thermostat-bar bends in one direction and completes the damper-closing circuit. If the room becomes too cool, the thermostat-bar bends in the other direction, and completes the damper-opening circuit.

EXAMPLE.—Clock pendulums will, due to temperature changes, vary in length, unless some compensating arrangement is provided.

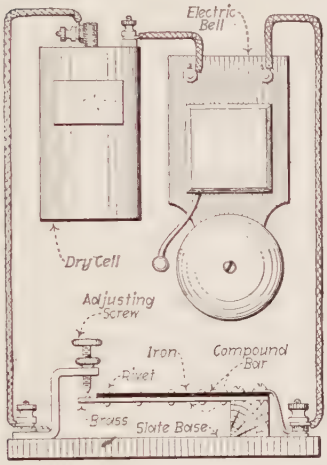


FIG. 188.—The thermostat.

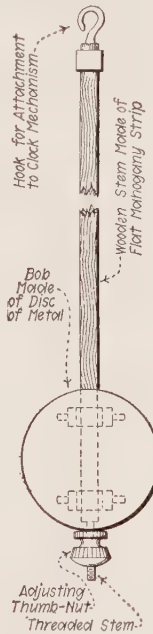

Hook for Attachment to Clock Mechanism
Wooden Stem Made of Flat Mahogany Strip
Bob Made of Disc of Metal
Adjusting Thumb-Nut Threaded Stem

FIG. 189.—Pendulum with wooden supporting stem to minimize effects of expansion and contraction.

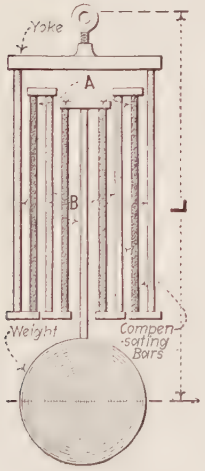


FIG. 190.—Compensated pendulum.

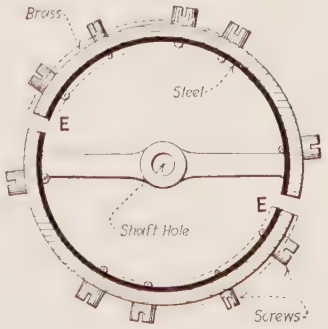


FIG. 191.—Compensated balance wheel for a watch.

Variation in pendulum length may cause the clock to run either too fast or too slow. Wooden stems (Fig. 189) are sometimes used because

(see Table 192) wood expands and contracts but slightly with changes in temperature. In the compensated pendulum (Fig. 190) there is, practically, no change in the effective length, L. When the metal bars B expand, they tend to lengthen the pendulum. But bars A, which are of a different metal, expand more than do bars B; this tends to shorten the pendulum. The lengths and the materials of A and B, are so selected that the actual pendulum length, L, is always, under reasonable temperature conditions, the same.

EXAMPLE.—The compensated balance wheel (Fig. 191) of a watch is so made that the ends E of the segments adjust themselves according to the temperature of the wheel.

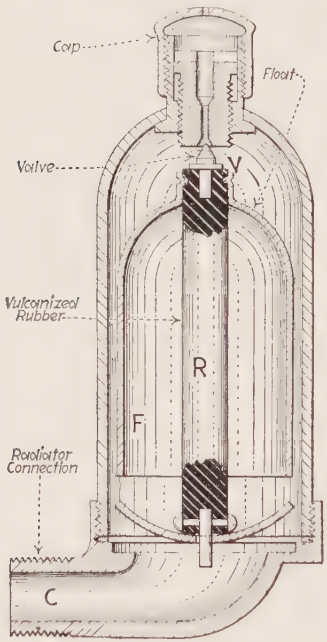


FIG. 192.—"Davis" steam-radiator air valve. (When R is surrounded by steam it expands and closes valve, V. Or, when water enters the chamber, float, F, rises and closes V.)

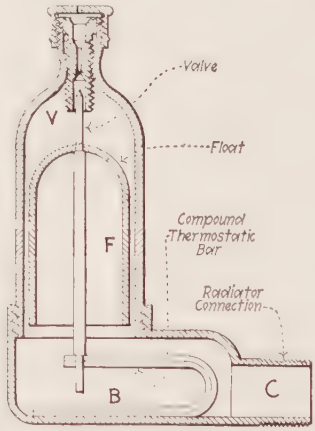


FIG. 193.—The "Onderdonk" radiator air valve. (Float F, closes valve, V, if water enters it. Bar, B, closes V after steam has entered it. The valve remains open when there is only cold air in it.)

Thereby, the watch is caused to run at a constant speed. If the balance wheel were not "compensated," the temperature would affect the speed of the watch. When warm, the oil would be thinner. Also, the diameter of the wheel and the length of the hair spring would be greater. When cool, these effects would be reversed. With a properly compensated wheel, they are, practically, of no consequence.

EXAMPLE.—AIR VALVES IN STEAM-HEATING RADIATORS (Figs. 192 and 193) may be automatically controlled by utilizing the compound-bar principle (Fig. 193) or by the expansion (Fig. 192) of a rubber post.

189. Expansion May Be Considered Under Three Different Headings: (1) *Lineal expansion, which is increase in length.*

(2) *Surface, superficial, or areal expansion, which is the increase in area of a surface when it is heated.* (3) *Volumetric expansion, which is increase in volume.* Obviously, there may likewise be lineal contraction, superficial contraction and volumetric contraction. Each of these phenomena will be considered.

190. The Coefficient Of Lineal Expansion is defined as the ratio of the increase in the length of a bar of material to its original length when the temperature of the material is increased 1° F. (or C.). A more practical definition is (Fig. 194) this: *The coefficient of lineal expansion is the increase in length, in inches, due to a temperature increase of* 1° *F. (or C.) in a bar of the material which was originally* 1 *in. long.* It is the increase in length, in inches per inch of original length, per degree temperature difference.

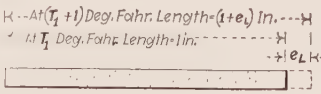


FIG. 194.—Illustrating coefficient of lineal expansion.

NOTE.—A COEFFICIENT OF EXPANSION CAN BE OBTAINED BY CONSIDERING THE DECREASE IN LENGTH, due to a temperature decrease, as well as by considering the increase in length, due to a temperature increase. Hence, the same coefficient is used in computing either contraction or expansion. Table 192 specifies some coefficients of lineal expansion.

191. A Coefficient Of Expansion Computed On The Basis Of The Above Definition Is Not Absolutely Accurate.—The exact value of an expansion coefficient depends upon the temperature at which the coefficient is determined. Likewise, the coefficient values given in Table 192 are not strictly accurate for every temperature. But the expansion coefficient values of any material differ, at different temperatures, from the values of the table so little that the errors which they may introduce through their application are of absolutely no consequence in any practical problem. A similar situation obtains for coefficients of areal or surface expansion (Sec. 199) and cubical-expansion coefficients (Sec. 202). For pure metals, the coefficient generally increases with the temperature. For alloys, there appears to be no general rule.

EXAMPLE.—As taken from the SMITHSONIAN PHYSICAL TABLES, the coefficient of lineal expansion of aluminum at 100° F. = 0000.,012,8; at 1,112° F. = 0.000,017,5.

192. Table Showing Coefficients Of Lineal Expansion Of Some Common Materials.—The tabulated values are equivalent to the expansion (or contraction), in inches, in each 1 in. original length, for each 1° F. increase (or decrease) in temperature. The values given here are the average values of the coefficient of lineal expansion between the temperatures 32 and 212° F.

Material, metals	Average coefficient of lineal expansion	Material, various	Average coefficient of lineal expansion
Aluminum	0.000,012,3	Brick	0.000,003,1
Aluminum bronze	0.000,009,4	Carbon, coke	0.000,003,0
Antimony	0.000,005,8	Cement, neat	0.000,006,0
Brass, cast	0.000,010,4	Concrete	0.000,008,0
Brass, wire	0.000,010,7	Glass, thermometer	0.000,004,5
Bronze	0.000,010,0	Glass, hard	0.000,003,3
Copper	0.000,009,3	Glass, plate and crown	0.000,005,0
German silver	0.000,010,2	Granite	0.000,004,8
Gold	0.000,008,2	Graphite	0.000,004,4
Iron, pure	0.000,006,7	Limestone	0.000,001,4
Iron, cast	0.000,005,9	Marble	0.000,006,5
Iron, soft forged	0.000,006,3	Masonry, from	0.000,002,5
Iron, wire	0.000,008,0	to	0.000,005,0
Lead	0.000,015,1	Porcelain	0.000,001,7
Magnesium	0.000,014,5	Rubber	0.000,042,8
Phosphor bronze	0.000,009,4	Vulcanite	0.000,040,0
Silver	0.000,010,7	Wood, oak:	
Solder	0.000,013,4	parallel to fiber	0.000,002,7
Steel, Bessemer:		across fiber	0.000,603,0
rolled hard	0.000,005,6	Chestnut:	
rolled soft	0.000,006,3	parallel to fiber	0.000,003,6
Steel, nickel (10% Ni)	0.000,007,3	across fiber	0.000,001,9
Tin	0.000,012,7	Ash:	
Type metal	0.000,010,8	parallel to fiber	0.000,005,3
Zinc	0.000,016,5	Pine:	
Zinc (cast)	0.000,010,6	parallel to fiber	0.000,003,0

193. Apparatus For The Determination Of The Coefficient Of Expansion utilizes the general principles indicated in Figs. 195 and 196. For tests where precise values are unnecessary, an equipment, similar to that of Fig. 195 may be used for

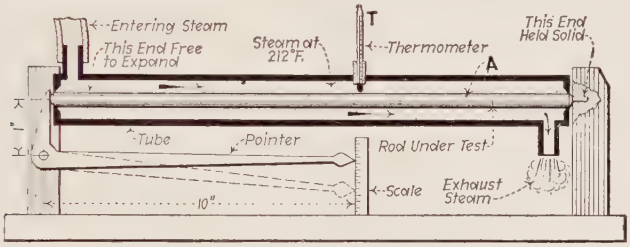


FIG. 195.—An apparatus for determining the coefficient of lineal expansion.

determining the lineal expansion of metals. For a very accurate determination, microscopes (Fig. 196) may be employed for measuring the increase in length.

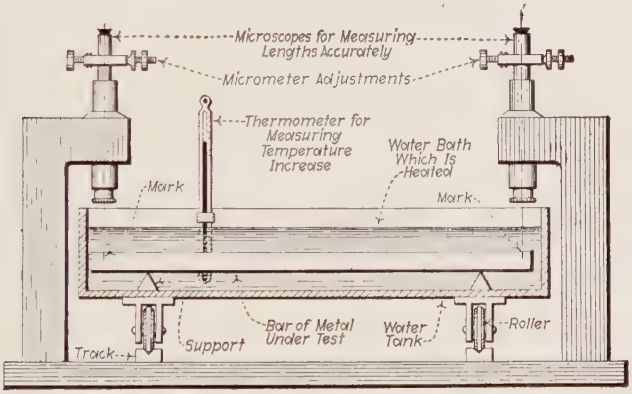


FIG. 196.—Equipment for precise coefficient-of-lineal-expansion determinations.

194. The Formula For Computing The Coefficient Of Lineal Expansion, which follows from the definition given in preceding Sec. 190 is:

$$e_L = \frac{L_2 - L_1}{L_1(T_2 - T_1)} \qquad \text{(coef. of linear expan.)} \tag{91}$$

or, since $l = {}_2 - L_1$:

$$e_L = \frac{l}{L_1(T_2 - T_1)} \qquad \text{(coef. of linear expan.)} \tag{92}$$

Wherein: e_L = the coefficient of lineal expansion. L_1 = the length of the material, measured in any unit, at the temperature T_1. L_2 = the length of the material, measured in the same unit as L_1, at temperature T_2. T_1 and T_2 = respectively, the temperatures in degrees Fahrenheit. l = increase in length due to expansion, in the same unit as L_1.

Note.—If The Original Length, L_1, Of The Material Is Unity, say 1 ft., and the temperature change is 1° F., then For. (91) becomes:

(93) $$e_L = L_2 - 1$$ (coef. of linear expan.)

Example.—At a room-temperature of 72° F., the length of the copper rod A, in Fig. 195, is 24 in. When the thermometer, T, reads 212° F., the rod length has increased 0.031,2 in. What is the coefficient of lineal expansion of copper? Solution.—Substituting in For. (92): $e_L = l/L_1(T_2 - T_1) = 0.031,2 \div [24 \times (212 - 72)] = 0.031,2 \div (24 \times 140) = 0.031,2 \div 3,360 = 0.000,009,3$ = *coefficient of lineal expansion of copper*, as shown in Table 192.

195. The Formula For Computing The Amount Of Lineal Expansion Or Contraction When An Object Is Heated Or Cooled is this:

(94) $$l = e_L L_1 T$$ (inches)

Wherein: l = increase in length due to expansion, or decrease in length due to contraction, in inches. L_1 = the length of the object before heating or cooling, in inches. e_L = coefficient of lineal expansion from Table 192. T = the temperature increase or decrease, in degrees Fahrenheit. (L_1 may be expressed in feet or any unit of lineal measure; then l will be in the same unit.)

Derivation.—By definition (Sec. 190) the coefficient of expansion e_L, is merely the expansion increase (or the contraction decrease) in inches, per inch original length, per degree temperature difference. Hence, to obtain the amount of expansion or contraction, it is merely necessary to multiply together the original length, the expansion coefficient and the temperature difference. These are the operations which For. (94) indicates.

Example.—An iron rod which is 10 ft. long has its temperature raised 25° F. What is its increase in length? Solution.—For iron, from Table 192, $e_L = 0.000,006,3$. Now, $10\ ft. = 10 \times 12\ in. = 120\ in.$ Substituting in For. (94), the increase in length is: $l = e_L L_1 T = 0.000,006,3 \times 120 \times 25 = 0.018,9\ in.$

Example.—A steel bridge is 872 ft. long. The variation of temperature in the locality, from the lowest winter to the highest summer tem-

perature, is 135° F. What is the maximum change in the length of the bridge? SOLUTION.—From Table 192, e_L for steel = 0.000,006,3. Now, 872 *ft.* = 872 × 12 *in.* = 10,464 *in.* The increase in length is: $l = e_L L_1 T$ = 0.000,006,3 × 10,464 × 135 = 8.9 *in.*

EXAMPLE.—What will be the change in length of a copper wire, strung between two poles which are set 120 ft. apart, when the temperature change is 120° F.? Neglect the elasticity and sag of the wire. SOLUTION. —From Table 192, e_L for copper wire = 0.000,009,3. Also, 120 *ft.* = 120 × 12 *in.* = 1,440 *in.* By For. (94): $l = e_L L_1 T$ = 0.000,009,3 × 1,440 × 120 = 1.6 *in.*

196. The Formula For Computing The Final Length Of A Material After It Has Been Heated (Fig. 197) is given below. This is the same as For. (94) except that the original length, L_1, is added in the right-hand member.

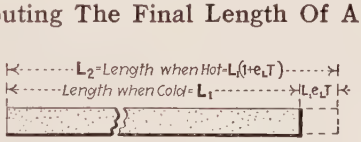


FIG. 197.—Lineal expansion of bar of any length.

(95) $$L_2 = L_1 + L_1 e_L T \quad \text{(inches)}$$

or:

(96) $$L_2 = L_1(1 + e_L T) \quad \text{(inches)}$$

or, substituting in (96) for T its equivalent $(T_2 - T_1)$:

(97) $$L_2 = L_1 + L_1 e_L (T_2 - T_1) \quad \text{(inches)}$$

EXAMPLE.—What will be the length of a cast-brass rod, at 200° F., if the length at 40° F., is 20 in.? SOLUTION —The lineal-expansion coefficient of cast-brass is, from Table 192, 0.000, 010,4. Now, substituting in For. (97): $L_2 = L_1 + L_1 e_L (T_2 - T_1)$ = 20 + [20 × 0.000,010,4 × (200 − 40)] = 20 + [0.000,208 × 160] = 20 + 0.033 = 20.033 *in.* = *length at* 200° F.

197. For Computing The Final Length Of A Material After It Has Been Cooled, For. (97) becomes:

(98) $$L_2 = L_1 - L_1 e_L (T_2 - T_1) \quad \text{(inches)}$$

198. Areal, Surface, Or Superficial Expansion (Fig. 198) is the increase in the area of a surface when it is heated. It is evident that the surface of any material will be larger, after heating than before, since the lineal expansion occurs in each of its two principal directions.

199. The Coefficient Of Areal Expansion is taken as *twice the coefficient of lineal expansion*. Strictly, this is not true.

But the error which the assumption introduces is of no consequence, practically.

Explanation.—Consider a copper plate (Fig. 198) which is 1 in. square. Its area is: $1 \times 1 = 1$ *sq. in.* Now if this sheet is heated, it will expand lineally in two directions: Both its length and width become greater by an amount e_L. Obviously, the sheet is now $(1 + e_L)$ in. square. Hence, its area is now $(1 + e_L) \times (1 + e_L) = (1 + e_L)^2 = 1 + 2e_L + e_L^2$. Substituting in this formula and taking the lineal expansion coefficient for copper as 0.000,009 from Table 192, the following results: $1 + 2e_L + e_L^2 = 1 + (2 \times 0.000,009) \div (0.000,009)^2 = 1 + 0.000,018 + 0.000,000,000,081 = 1.000,018,000,081 =$ *areal expansion coefficient for copper.* It is evident that the value equivalent to e_L^2, which is 0.000,000,000,081, is so small that its omission from the coefficient would result in no material error. It is, therefore, apparent that for all practical purposes it is sufficient to assume that coefficients of areal expansion may be taken as twice those of lineal expansion, which are given in Table 192.

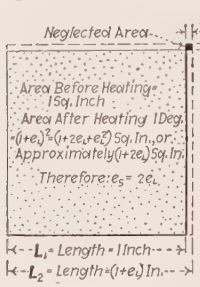

Neglected Area
e_L^2
Area Before Heating = 1Sq. Inch
Area After Heating 1Deg. $(1+e_L)^2=(1+2e_L+e_L^2)$ Sq. In., or: Approximately $(1+2e_L)$ Sq. In.
Therefore: $e_S = 2e_L$
L_1 = Length = 1 Inch
L_2 = Length $=(1+e_L)$ In.

Fig. 198.—Illustrating derivation of coefficient of areal expansion.

200. The Formula For Computing Increase In Area, Due To Areal Expansion, which follows from the statements of Secs. 198 and 199, is this:

$$A = e_S A_1 T \qquad \text{(square inches)} \tag{99}$$

Wherein: A = increase in area, due to expansion, or decrease in area, due to contraction, in square inches. e_S = coefficient of areal expansion = $2 \times$ *lineal-coefficient value* from Table 192. T = the temperature increase or decrease in degrees Fahrenheit. A_1 = initial area in square inches. A_1 For. (99) may be expressed in square feet or in any unit of areal measure. Then A will be in the same unit.

Example.—A section of street paving which measures 20×24 ft. is subjected to a temperature difference of 135° F. If the lineal-expansion coefficient of the material is 0.000,003, what will be the change in area? Solution. The areal-expansion coefficient will be $2 \times 0.000,003 = 0.000,006$. Therefore, the change in area will be, For. (99): $A = e_S A_1 T = 20 \times 24 \times 0.000,006 \times 125 = 0.36$ *sq. ft.*

201. Cubical, Cubic, Or Volumetric Expansion (Fig. 199) is the increase which occurs in the volume of a substance when the substance is heated. Cubical contraction is the decrease

in volume when the substance is cooled. It is evident from Fig. 199 that when a substance is heated, it expands lineally in all three directions. The change in volume which results is just as definite as a change of length due to lineal expansion.

202. The Coefficient Of Cubical Expansion (Table 207) is assumed to be equal to three times the coefficient of lineal expansion, certain values for which are given in Table 192. While this assumption (see explanation below) is not absolutely accurate, it is sufficiently so for ordinary use.

EXPLANATION.—Assume that the 1-in. cube of Fig. 199 has, before heating, a volume of $1^3 = 1$ *cu. in.* After the temperature of the cube has been increased 1° F., the cube expands the distance e_L in each of the three lineal directions. Hence, the length of each of its sides becomes $(1 + e_L)$. Now the volume of the heated cube will be $(1 + e_L)^3 = (1 + 3e_L + 3e_L^2 + e_L^3)$ cu. in. Now, as demonstrated in explanation under Sec. 199, the values equivalent to $3e_L^2$ and e_L^3 will be so small as to be inconsequential. Hence, they may be disregarded. Therefore, the volume of a heated cube can, with very small error, be taken as $(1 + 3e_L)$ cu. in. In other words, $3e_L$ is the *coefficient of cubical expansion.*

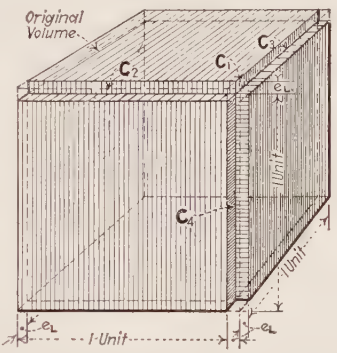


FIG. 199.—Illustrating the cubical coefficient of expansion (the volume of the corners C_1 C_2 C_3 and C_4 are so small as compared with the volume of the whole that they are disregarded in computing the cubical coefficient of expansion).

203. The Formula For Computing The Change In Volume, Due To Cubical Expansion which follows from the preceding discussion and statements is:

$$V = 3e_L V_1 T \qquad \text{(cubic inches)} \tag{100}$$

Wherein: V = change in volume, due to expansion or contraction, in cubic inches. V_1 = the original volume of the substance, in cubic inches. Other symbols have the meanings hereinbefore specified. V_1 (For. 100) may be expressed in cubic feet or in any other unit of cubical measure. Then, V will be in the same unit.

EXAMPLE.—A block of concrete is 30 ft. wide, 17 ft. high, and 4 ft. thick. What will be the change in its volume, when its temperature is

changed 50° F.? Solution.—From Table 192, the *lineal-expansion coefficient for concrete* = 0.000,008. Then the *cubical-expansion coefficient* = 3 × 0.000,008 = 0.000,024. The *original volume* = 30 × 17 × 4 = 2,040 *cu. ft.* Now, substituting in For. (100): $V = 3e_L V_1 T$ = 0.000,024 × 2,040 × 50 = 2.45 *cu. ft.*

204. The Formula For Computing The Volume Of Any Substance, After It Has Been Heated Or Cooled, Is:

(101) $$V_2 = V_1(1 + e_V T)$$ (cubic inches)

Wherein: V_2 = final volume, in cubic inches. V_1 = original volume, in cubic inches. e_V = coefficient of cubical expansion from Table 207, or $e_V = 3e_L$, as taken from Table 192. T = the temperature increase or decrease, in degrees Fahrenheit.

205. The Expansion Of Liquids has been mentioned in the preceding discussion (Sec. 57) of thermometers. All liquids, with the exception of water, as explained below, expand when heated and contract when cooled. This property renders possible the mercury thermometer. Due to their expansion, all liquids increase in volume when heated (except some when near the freezing point). In general for any given solid the change in volume per degree temperature difference is practically the same, regardless of the original temperature under consideration. But for liquids this is not true. With different liquids the change in volume, per degree temperature difference, varies somewhat according to the temperature under consideration; the coefficient is greater at high than at low temperature. However, for practical engineering purposes, average values (Table 207) may be taken.

Note.—The Expansion Of Liquids Is Cubical.—Hence, the preceding formulas which were given for computing cubical expansion are the ones which are applied for figuring the expansion of liquids.

206. Coefficients Of Cubical Expansion of Liquids Are Difficult Of Accurate Determination.—The liquid under observation must be contained in a vessel, the material of which has an expansion coefficient different from that of the liquid. However, compensation for the possible error, thus introduced, may be made.

Example.—Compensated clock pendulums may be made (Fig. 200 and 201) with mercury, in glass vessels, constituting a "bob." When the rod, R, expands downwardly, the mercury, M, expands upwardly.

Thereby, assuming correct design, the effective length of the pendulum remains unchanged.

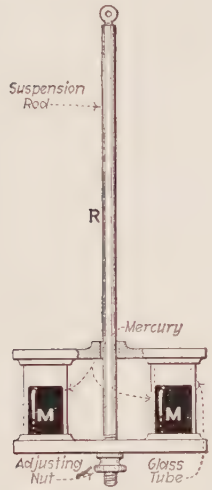


FIG. 200.—The mercury-compensated pendulum.

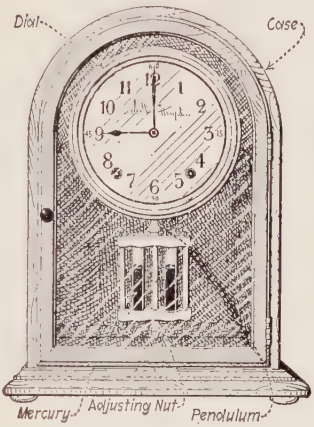


FIG. 201.—Clock equipped with mercury-compensated pendulum.

207. Table Showing Coefficients Of Cubical Expansion Of Some Common Liquids And Solids.

Material	Coefficient of cubical expansion	Material	Coefficient of cubical expansion
Acetic acid	0.000,80	Olive oil	0.000,41
Alcohol (ethyl)	0.000,61	Petroleum	0.000,55
Alcohol (methyl)	0.000,80	Sodium chloride:	
Benzine	0.000,77	1.6 per cent. solution	0.000,60
Benzol	0.000,70	26 per cent. solution	0.000,24
Calcium chloride 5 to 50 per cent. solution	0.000,28	Sulphuric acid	0.000,27
Chloroform	0.000,77	Sulphuric acid, 50 per cent. solution	0.000,45
Ether	0.001,21	Turpentine	0.000,56
Glycerine	0.000,28	Water	0.000,10
Hydrochloric acid	0 000,27	Ice (4 to 30° F.)	0.000,62
Hydrochloric acid 50 per cent. solution	0.000,50	Paraffin wax	0.000,61
Mercury	0.000,10	Rocksalt	0.000,67
		Sulphur	0.000,40

Example.—An open tank contains 6,700 gallons of water of 60° F. How many gallons will it contain, if the temperature of the water is increased to 105° F.? Solution.—From Table 207, the cubical coefficient of expansion of water is 0.000,1. The *change in temperature* = $T = 105 - 60 = 45°$ F. Now, substituting in For. (101): $V_2 = V_1(1 + evT) = 6{,}700 \times [1 + (0.000{,}1 \times 45)] = 6{,}730.15$ *gal.*

208. Liquids Are Practically Incompressible.—The amount which they may be compressed is exceedingly small. Hence, when the liquids which completely fill closed vessels are heated, the resulting pressure, due to their expansion, may be enormous. Serious distortions and ruptures in containing vessels may result through disregard of this fact.

Example.—In hot-water heating systems an *expansion tank* is located near the top of the building; see Div. 17. Into this tank, the water expands, when heated. If the expansion tanks or other suitable arrangements were not provided, the enormous pressure which would be developed in the system by heating of the water might cause valve leakage, and the breaking of radiators, valves, or fittings.

209. The Peculiar Expansion And Contraction Of Water (Fig. 202) will now be considered. Since water is the most common liquid it will be discussed herein at some length. All liquids

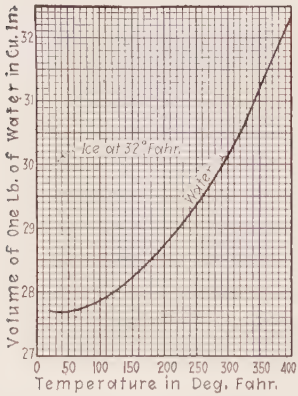


Fig. 202.—Graph showing change in volume of water as it is heated.

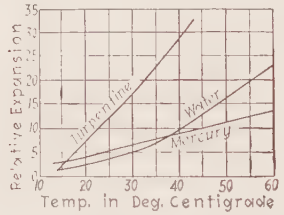


Fig. 203.—Expansion of turpentine as compared to water and mercury (although the graphs for mercury and turpentine appear to be straight lines, they actually curve somewhat. The curvature is too small to be detectable with the scales shown.)

with certain exceptions, water for example, (Figs. 203 and 204) contract when cooled. When water is cooled its volume changes considerably, as is shown by the graph (Fig. 202). But at about 39° F. it is (Fig. 205) at maximum density. That is, it weighs more, per unit of volume, at this tem-

perature than at any other temperature. If it is cooled below this temperature, it begins to expand. This is a peculiar characteristic of water. After cooling to 32° F. it solidifies into ice and the freezing is accompanied by farther expansion.

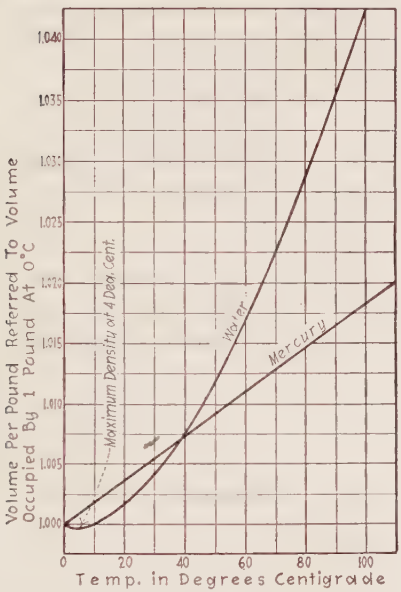


Fig. 204.—Graph comparing the change in densities of mercury and water at different temperatures.

Note.—Expansion, At Freezing Temperature, Is A Very Important Attribute

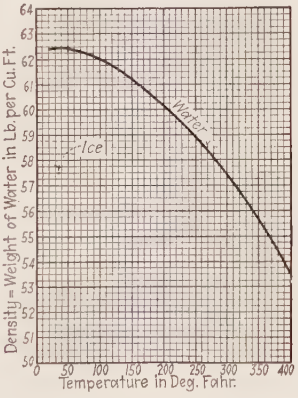


Fig. 205.—Change in weight of water as temperature is changed.

Of Water.—It is Nature's provision against the oceans, lakes and rivers freezing to the bottom. Ice forms at the surface of the water and being lighter than water remains there. Thus it covers or blankets the water beneath. It prevents the lower strata of water from becoming cooled to the freezing stage.

210. When Water At A Temperature Above 39° F. Is Heated, It Expands.—Its density then diminishes and it becomes "lighter." That is, its weight per unit of volume decreases. This property is very important in certain heating processes.

Example.—When heat is applied to the bottom of a tank which contains water, a circulation of the water immediately ensues. The stratum of water in contact with the bottom is heated. Thus it is caused to expand. It becomes less dense, or "lighter" than the water above. The cooler, and heavier, water at the top then circulates to the bottom. It thereby displaces the heated water, which ascends to the surface.

Hot water may thus be drawn from the top of a tank before the entire mass of water is heated.

211. The Expansive Property Of Water Is Utilized In Hot-water Heating Systems.—The cooler, and heavier, water flows into the boiler, or heating element, at the bottom. Therein it becomes (Fig 126) heated and expanded. It then flows through the radiators and gives up some of its heat to the air in the rooms. When it leaves the radiators, it is again comparatively cool. It then flows down to the boiler through the return pipe. A continuous circulation is thus maintained.

212. Differences Of Expansion And, Therefore, Of Density Between Different Parts Of A Volume Of Water Cause Currents To Circulate Therein.—These are called *convection currents.* The rapidity with which water may be heated depends upon the rapidity of these currents. Without them it would be difficult to heat water in any form of vessel, whether a teakettle on a kitchen stove or a steam boiler in a power plant. Water is a very poor conductor of heat. Hence, this property (conduction) is not effective in carrying heat quickly to all parts of a mass of water.

213. Freezing Water Exerts An Enormous Expansion Force (Figs. 182 and 206). Ordinarily, one cubic foot of water becomes about 1.085 cu. ft. of ice. The expansion is about 8.5 per cent. The expansion of a body of water, by freezing into ice, thus amounts to more than one-twelfth of the initial volume of the water. If water is frozen in a closed vessel, the expansion of the ice thus formed may, and generally will, rupture the vessel, even though the vessel be made of iron or steel.

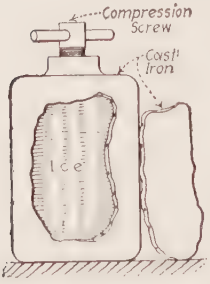


Fig. 206.—The result of water frozen in a closed cast-iron vessel. (Actually the expanding ice, which breaks a vessel, issues from the hole which it makes as shown in Fig. 182.)

Example.—A gallon of water contains 231 cu. in. Hence, if a gallon of water freezes to ice at 32° F., the volume of the ice will be $231 \times 1.085 = 249.64$ cu. in.

Note.—The Molecules Of Water In The Form Of Ice Are Closer Together Than Are The Molecules Of Liquid Water.— Thus the behavior of water, when passing from

the liquid to the solid state, presents no exception to the general law (Sec. 50) which governs molecular action in substances from which heat is extracted. The apparent anomaly observed in the expansion of ice is explained on the hypothesis that the molecules of ice group themselves into crystals. Thus, while the molecules are more compactly arranged in the ice crystals than in the liquid water, the crystals themselves are separated by comparatively large spaces. Hence, the net effect of the crystalline grouping of the molecules is an increase instead of a diminishment of volume.

214. The Behavior Of Metals When Changing From The Liquid To The Solid State will now be considered. Besides water, cast iron, antimony, and bismuth are, perhaps, the most common substances which increase in volume when freezing or solidifying. When molten cast iron freezes or solidifies in a foundry mold, it expands. However, cast iron contracts about 1 per cent. while cooling from its freezing point to ordinary temperature. Hence, it is often said that cast iron shrinks. Unless proper precautions are taken, this shrinkage may break a casting (Fig. 207). With other metals (Sec. 187) a contrary effect will be noted; that is, they decrease in volume when solidifying. A few common examples of this latter class are mercury, gold, and silver.

Note.—The Expansive Solidification Of Antimony And Its Low Expansion Coefficient Render It Useful As A Type-metal Ingredient.—The sharp outlines requisite in printing type could not be obtained if the cast metal were to contract while solidifying. Ordinary type metal is an alloy of lead, antimony, and copper. The tendency of the antimony to expand neutralizes the tendency of the other ingredients to contract. Thus the volume of the molded metal continues constant during transition from the molten to the solid state.

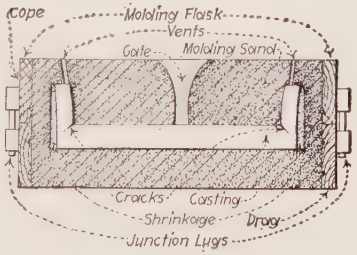


Fig. 207.—Shrinkage causes casting to crack in mold.

Note.—Expansion Of Antimony While Cooling From The Liquid To The Solid State is due to a crystalline arrangement of the molecules similar to that which occurs (note subjoined to Sec. 213) in the freezing of water.

Note.—The Graduation Marks On A Patternmakers' Rule Are Spaced Farther Apart Than Are Those On An Ordinary Standard

Rule.—The increased spacing, on rules used in the making of patterns for iron castings, amounts to $\frac{1}{8}$ in. per ft. This is to insure that the patterns will be made enough larger, than the required castings, to compensate for shrinkage of the solid iron in cooling.

Note.—The Excessive Contraction Of Gold And Silver While Cooling From The Liquid To The Solid State Prevents Accurate Casting With These Metals.—The shrinkage of the metal in the mold will invariably result in producing warped castings, with rounded and blunted edges and corners. Hence, as stated in Sec. 187, in the minting of gold and silver currency, the coins are stamped out of the solid metal with steel dies.

215. Table Showing Approximate Lineal Shrinkage Of Castings And Forgings (From Marks' Handbook, page 294).

Metal	Shrinkage ratio	Multiplier	Metal	Shrinkage ratio	Multiplier
Bar iron, rolled.	1:55	1.018,2	Iron, fine grained.	1:72	1.013,9
Bell metal.....	1:65	1.015,4	Lead.....	1:92	1.010,9
Bismuth.....	1:265	1.003,8	Steel, cast.....	1:50	1.020,0
Brass.....	1:65	1.015,4	Steel, puddled...	1:72	1.013,9
Bronze.....	1:63	1.015,9	Steel, wrought..	1:64	1.015,6
Cast iron.....	1:96	1.010,4	Tin.....	1:128	1.007,8
Gun metal....	1:134	1.007,5	Zinc, cast.....	1:62	1.016,1

Example.—The shrinkage of a bell-metal casting, while the metal is cooling in the mold, amounts to $1 \div 65 = 0.015{,}4$ *in. per inch of length of the final casting.* Hence, the pattern for a bell-metal casting should be 1.015,4 times as long as the required casting.

Example.—An iron casting is required to be 3 ft. long, 8 in. wide, and 2 in. thick. What should be the dimensions of the mold? What will be the percentage of shrinkage in the casting? Solution.—The *volume of the casting* $= (3 \times 12) \times 8 \times 2 = 576$ *cu. in.* By Table 215 each dimension must be multiplied by 1.010,4. Hence, the length of the mold $= 3 \times 1.010{,}4 = 3.031{,}2$ *ft.*, the width $= 8 \times 1.010{,}4 = 8.083{,}2$ *in.*, and the depth $= 2 \times 1.0104 = 2.0208$ *in.* Then, *the volume of the mold* $= (3.0312 \times 12) \times 8.0832 \times 2.0208 = 594.16$ *cu. in.* Hence, *the percentage of shrinkage* $= [(594.16 - 576)/594.16] \times 100 = 3.06$ *per cent.*

216. There Are Two Conditions Under Which A Solid May Expand Or Contract: (1) *The expansion or contraction may be entirely unopposed by counteracting forces.* (2) *The expan-*

sion or contraction, or the tendency thereto, may be opposed or restrained in some manner by counteracting forces. Each of these conditions will be discussed in the following sections. Only unrestrained expansion and contraction have hitherto been considered.

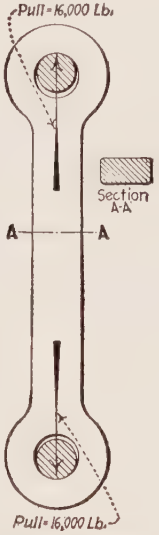


FIG. 208.—Stress due to tension.

217. A Study Of The Phenomena Of Restrained Expansion And Contraction Involves Consideration Of Stresses And Strains In Materials.—When any substance, as a metal wire, is subjected to a pulling force, the force tends to strain the substance by stretching or elongating it. Coincidentally, a stress, which tends to oppose deformation by the pulling force, develops within the substance. When any substance, as a mass of rubber, is subjected to a pressing force, the force tends to strain the substance by crowding its particles closer together. In this case also, a stress, which resists the applied force, develops within the substance. So likewise, when any substance, as a boiler rivet, is subjected to the straining action of a shearing force, a stress develops within the substance. When a substance is subjected (Fig. 208) to a pull or *tension*, the stress developed in the substance thereby is called a *tensile stress.* When a substance is subjected (Fig. 209) to

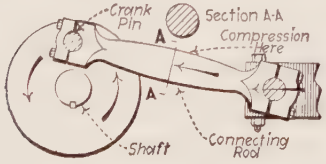


FIG. 209.—Stress due to compression.

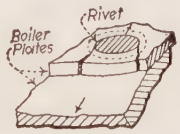


FIG. 210.—Showing a piece being sheared from boiler plate by rivet.

pressure or *compression*, the stress developed in the substance thereby is called a *compressive stress.* When a substance is subjected (Figs. 210 and 211) to a shearing force, the stress developed thereby is called a *shearing stress.* Tensile, com-

pressive, and shearing stresses are usually expressed in terms of the forces which are applied to produce them, divided by the number of area units in the cross-section of the substance where it opposes the force.

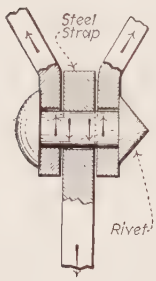


Fig. 211.—Stress due to shear.

Examples.—If a wire of 0.1-sq. in. cross-section suspends a load of 1,600 lb., the *tensile stress* in the wire is $1,600 \div 0.1 = 16,000$ *lb. per sq. in.* If a steel bridge-rod, of 3-sq. in. cross-section, is subjected to a pull of 150,000 lb., the *tensile stress* in the rod is $150,000 \div 3 = 50,000$ *lb. per sq. in.* If an iron column of 4-sq. in. cross-section supports a load of 4,000 lb., the *compressive stress* in the column is $4,000 \div 4 = 1,000$ *lb. per sq. in.*

Note.—"Stress" And "Strain" Are Not Synonymous Terms. A *stress*, as explained above, is the internal opposing force which develops within a substance when an external force, tending to deform the substance, is applied. A *strain* is the deformation, or charge of shape, of a substance within which a compressive or tensile stress has been developed by application of an external force. As noted above, a stress is measured by the intensity of the applied force and by the cross-sectional area of the substance which sustains the force. The corresponding (total) strain is expressed in terms of the change of dimension of the substance, in the line of direction of the applied force. Furthermore, since, under tensile or compressive stress, each inch (or foot) of length of the substance is changed by the same amount, the strain can be expressed as a decimal—it is then called the *unit strain* or simply the *strain*—that is, the number of inches (or feet) that each inch (or foot) has been lengthened or shortened.

Example.—If a metal wire, of 10-in. length, is elongated under a pull to a length of 10.1 in., the total strain in the wire is: $10.1 - 10 = 0.1$ *in.* Then *the unit strain = strain, in inches per inch of original length* $= 0.1 \div 10 = 0.01$.

218. Material Bodies Generally Tend To Resume Their Original Forms When Released From Forces Which Have Produced Strains In Them.—A rubber band may be stretched to a considerable length, but it will, apparently, instantly resume its original dimension when the stretching force is removed. Most materials, however, will not, when strained beyond certain limits, return entirely to their original shapes. In such cases the materials are said to have taken *permanent set*. Some materials acquire this condition under compara-

tively small loads. Others are permanently deformed only by application of very great loads.

219. Strains Are, Within Certain Limits, Directly Proportional To The Stresses From Which They Result.—That is to say, there is, usually (below the elastic limit, Sec. 220) for each substance, a definite ratio between a stress produced in the substance and the resulting deformation or strain. This ratio is called the *coefficient of elasticity* of the substance. See Table 221 for values. In the notation used in this book, the coefficient or elasticity will be denoted by E. Hence the formula:

$$E = \frac{stress}{strain} = \frac{lb.\ per\ sq.\ in.}{stretch\ per\ inch} \quad \text{(lb. per sq. in.)} \tag{102}$$

NOTE.—"MODULUS OF ELASTICITY" AND "YOUNG'S MODULUS" are synonymous terms for *coefficient of elasticity.*

EXAMPLE.—A steel rod, 20 in. long, when under a stress of 60,000 lb. per sq. in. stretches 0.04 in. What is the coefficient of elasticity of steel? SOLUTION.—By For. (102): $E = stress \div strain = lb.\ per\ sq.\ in. \div stretch\ per\ inch = 60{,}000 \div (0.04 \div 20) = 30{,}000{,}000\ lb.\ per\ sq.\ in.$

EXAMPLE.—A bridge member of 0.5-sq. in. cross-section and 40-ft. length, elongates 0.25 in. under a certain load. If $E = 30{,}000{,}000$ lb. per sq. in, what is the load? SOLUTION.—By a transposition of For. (102): $Stress = E \times strain = lb.\ per\ sq.\ in. = E \times stretch\ per\ inch = 30{,}000{,}000 \times 0.25 \div (12 \times 40) = 15{,}625\ lb.\ per\ sq.\ in.$ Hence, the load $= 15{,}625 \times 0.5 = 7{,}813\ lb.$

EXAMPLE.—The tension in a steel telephone-wire, 100 ft. long, is 525 lb. The cross-sectional area of the wire is 0.006,4 sq. in. $E = 30{,}000{,}000$ lb. per sq. in. How much has the wire stretched? SOLUTION.—By a transposition of For. 102: $Strain = stress \div E = stretch\ per\ inch = lb.\ per\ sq.\ in. \div E = (525 \div 0.006{,}4) \div 30{,}000{,}000 = 0.002{,}73\ in.$ Hence, the wire has stretched $0.002{,}73 \times 100 \times 12 = 3.28\ in.$

220. When A Material Body Is Stressed Beyond A Certain Value Or "Limit," The Resulting Strain, Per Unit Of Load Increment, Becomes Greater Than Formerly.—The strain then ceases to be directly proportional to the stress (Sec. 219). When this limit is reached the ratio of *the stress in the body to the strain or deformation of the body* will be less than the similar ratio for stresses below this limit. The stress above which the strain ceases to be directly proportional to the stress, is called the *elastic limit* of the material. When a body is stressed beyond its elastic limit and the stress is then relieved

(by removing the force which produced the stress), the body will be found to have suffered a permanent deformation. Stresses below the elastic limit do not cause any permanent deformation, or "set." Hence, when a stress is permitted to exceed the elastic limit, the body ceases to be truly "elastic" —that is, it ceases to be capable of returning to its former dimensions. Hence, the term "elastic limit" is truly significant. (See the author's STEAM BOILERS for graphs and a more complete discussion.)

NOTE.—THE "ULTIMATE STRENGTH" OF A MATERIAL is found by dividing the maximum force, which the material sustains during a test carried on until rupture occurs, by the original cross-sectional area of the test piece at the point of the rupture. In actual practice, the cross-sectional area usually changes before rupture occurs. Therefore, the maximum stress in the material may somewhat exceed the value of the "ultimate strength" which is computed as indicated above.

221. Table Showing Coefficients Of Elasticity For Different Materials.

Materials	*E* lb. per sq. in.	Materials	*E* lb. per sq. in.
METALS		WOODS	
Aluminum	11,000,000	Ash	1,600,000
Brass, cast	9,000,000	Birch	1,300,000
Brass wire	14,000,000	Oak	1,500,000
Phosphor bronze	14,000,000	Teak	2,410,000
Copper wire	16,000,000	Walnut	306,000
Iron, cast	12,000,000	Pine	1,900,000
Iron, wrought	27,000,000		
Lead	1,000,000	MISCELLANEOUS	
Tin, cast	4,000,000	Slate	14,000,000
Steel	30,000,000	Glass	8,000,000

222. Expansion And Contraction Of Restrained Solids will now be considered. If the tendency of a body of solid material to expand or contract is restrained in some manner, a stress will develop within the body. The result of such restraint will be the same as though the body were stressed by an external force. The stress produced by restraint of the

tendency to expand or contract is exactly equal to the stress which would be set up in the body if it were, by some outside force, either elongated or compressed the amount which it tends to expand or contract.

Explanation.—Suppose a piece of copper is held tightly in a vise and is heated by means of a torch. Due to its absorption of the heat, the copper tends to expand, say, 0.01 in. But the clamping action of the jaws of the vise counteracts this tendency. Then the resultant condition within the piece of copper is the same as though the copper had first been heated and had then been squeezed or compressed 0.01 in. by a further tightening of the vise. By preventing the copper from responding to the expansion tendency produced by the heat, a compression stress, equal to that which would have been produced by compressing the copper 0.01 in., has been developed within the copper bar.

Note.—The Influence Of External Forces In Hindering Free Expansion And Contraction Of Structural Members Demands Close Attention.—Serious accidents may result from ignoring it. Bridge members may fail; see Figs. 180 and 181 for expansion joints. Dangerous stresses may be set up in steam boilers. Pavements may

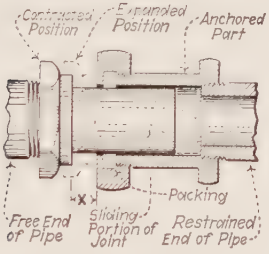


Fig. 212.—Expansion joint to allow pipe to expand.

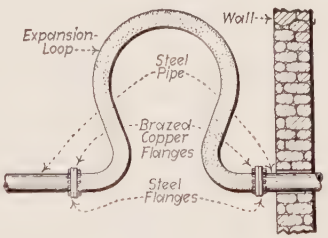


Fig. 213.—Expansion loop in high-pressure steam line.

become distorted, or may even explode. Long pipe-coil radiators may buckle and leak and fittings in steam-piping systems may be strained and broken, unless proper arrangements which allow for expansion (Figs. 212 and 213) are provided.

223. When The Expansion Or Contraction Tendency Of A Solid Is Restrained Or Counteracted, A Strain Practically Proportional To The Coefficient Of Expansion Of The Material And To The Temperature Change Is Produced.—The piece of copper in the above explanation (Sec. 222) is compressed exactly the same amount that it would have expanded had it been free to do so. Hence, if the coefficients of expansion and

elasticity of the material are known, and the temperature-change is observed, the stress, due to restrained expansion or contraction, in a solid may be calculated.

Explanation.—By referring to Fig. 197, it is evident that the expansion of an unconstrained bar of original length L_1 is $L_1 e_L T$, and its length after heating is $L_1(1 + e_L T)$. If, now, the bar is compressed to its original length, this expansion length ($L_1 e_L T$) will be the amount of the total strain. Hence the unit strain will be: (*total strain*) ÷ (*length before straining*) $= L_1 e_L T \div L_1(1 + e_L T) = e_L T \div (1 + e_L T)$.

Now, the expansion coefficient e_L is so small that the term $e_L T$ seldom even approaches 1 per cent. Hence, it is ordinarily sufficient to say that the *unit strain* $= e_L T \div 1 = e_L T$, which is very nearly true.

Therefore, the strain is, as previously explained, practically proportional to the coefficient of expansion and the temperature change. Hence, the following equation may be written:

$$\frac{\textit{lb. per sq. in. stress}}{\textit{unit strain}} = \frac{\textit{lb. per sq. in. stress}}{e_L T} \tag{103}$$

Wherein: e_L = coefficient of lineal expansion = expansion or contraction, in inches, per inch original length of body per degree Fahrenheit change in temperature. T = temperature change, in degrees Fahrenheit. But the first member of this equation gives (Sec. 219) the coefficient of elasticity. That is:

$$\frac{\textit{lb. per sq. in. stress}}{\textit{unit strain}} = E \qquad \text{(lb. per sq. in.)} \tag{104}$$

Hence, substituting (104) in (103):

$$E = \frac{\textit{lb. per sq. in. stress}}{e_L T} \qquad \text{(lb. per sq. in.)} \tag{105}$$

Transposing (105) there results:

$$\textit{lb. per sq. in. stress} = E e_L T \qquad \text{(lb. per sq. in.)} \tag{106}$$

Or, expressing the stress in terms of the equivalent restraining force, in pounds, and transposing, there results the following formula:

$$F = E e_L T A \qquad \text{(pounds)} \tag{107}$$

Wherein: F = the restraining force, in pounds. A = the cross-sectional area, in square inches, which offers resistance to the force.

Example.—In the explanation subjoined to Sec. 222, what compressive-force is exerted by the vise-jaws if the temperature of the copper is raised 200° F.?

Solution.—For copper, $e_L = 0.000{,}009{,}3$ and $E = 16{,}500{,}000$ lb. per sq. in. By For. (106), *stress* $= E e_L T = 16{,}500{,}000 \times 0.000{,}009{,}3 \times 200 = 30{,}690$ *lb. per sq. in.*

Example.—The joints of the steel rails in a street-car track are welded for a distance of 1,320 ft. The job is done on a summer day.

The temperature of the weather drops 35° F. during the following night. (1) What is the resulting tension in the rails if the ends cannot give? (2) How many inches will the track shorten if the ends are left free? SOLUTION.—For steel, $e_L = 0.000,006,5$ and $E = 30,000,000$ lb. per sq. in. (1) By *For.* (106), *stress* $= Ee_LT = 30,000,000 \times 0.000,006,5 \times 35 = 6,825$ lb. per sq. in. (2) By *For.* (94), $l = L_1e_LT = 1,320 \times 12 \times 0.000,006,5 \times 35 = 3.6$ *in.*

QUESTIONS ON DIVISION 7

1. Give some examples of materials expanding in length.

2. Give examples of peculiar constructions designed to allow for expansion.

3. What is a *coefficient of lineal expansion?* How may it be used?

4. State the formula for computing the length of a bar of material that has been heated a given amount.

5. What is *areal expansion?*

6. State and explain the formula for computing the area of a sheet of material that has been heated. Does this formula give an exact value? Why?

7. State and explain the formula for computing cubical expansion. Does this formula give an exact value? Why?

8. What is a *tensile stress?* A *compressive stress?*

9. In what units are tensile and compressive stresses expressed?

10. What is *shearing stress?*

11. What is meant by *stress? Strain?*

12. What is meant by the *coefficient of elasticity* of a material?

13. What is meant by *permanent set?*

14. State and explain the uses of coefficients of elasticity in computations relating to structural materials.

15. Why are openings left between the ends of the rails of railroad tracks? Why is tar placed in the joints of cement pavements?

16. If a metal body is so confined that it cannot expand, what is the result when it is heated?

17. Why should water in glass jars not be left out of doors in winter?

18. Why are the water-barrels which are placed on railroad bridges, for protection against fire, filled with salt-water?

19. State and explain the formula for computing the stress set up in a body wherein expansion or contraction is restrained.

20. Do the molecules of freezing water obey the general law which governs molecular action in substances from which heat is withdrawn? What is this law?

21. Why does ice float on water?

22. How do ice formations act to prevent lakes and rivers in cold latitudes from freezing to the bottom?

23. What causes the water to circulate in a hot-water heating system?

24. Why is antimony used in type metal?

25. Why would it be difficult to heat water if no convection currents were set up in the mass of water?

26. Why is it difficult to determine the coefficients of expansion of liquids?

27. Is the coefficient of expansion constant for each liquid?

28. Is there any difference in the cubical expansion of a liquid as compared with that of a solid?

29. What may happen if heat is applied to a vessel which encloses a liquid?

30. How is the shrinkage of iron castings compensated for in making the molds?

31. Are liquids compressible? What would be the probable effect of freezing water in a glass jar, if water were highly compressible?

32. When a boiler is cold, the water stands at a certain height in the gage glass. When the boiler is fired up, the water gradually rises to a higher level Why?

PROBLEMS ON DIVISION 7

1. A brass test-rod (*A*, Fig. 195) is 26.1 in. long at a temperature of 40° F. How long will it be when heated to 212° F.? What distance will the pointer move over the scale?

2. If a glass test-rod (*A*, Fig. 195) is inserted in the steam tube, what will be the expansion for the same temperature conditions as in Prob. 1?

3 A steel girder bridge (Fig. 180) is 98 ft. long. What distance will the movable shoe travel on the rollers when the temperature of the weather changes from 30° below 0° F. to 110° above 0° F.?

4. In bridge construction it is customary, if the length of the bridge is less than 50 ft., to fasten both ends rigidly. How much would a 50-ft. steel bridge, so secured, tend to expand lengthwise for each degree rise of temperature? If the bridge were set on piers, what would be the effect of this expansion tendency?

5. A long pipe line contains a series of expansion joints (Fig. 212). The joints are spaced 300 ft. apart. The line is designed to convey steam at a temperature of 300° F. It is erected in an atmospheric temperature of 50° F. In the adjustment of the joints, what should be the least distance, *X*, to allow for slip as the line expands?

6. A strip of concrete pavement is to be 30 ft. wide. It is to contain a series of expansion joints spaced at 100-ft. intervals A temperature range of 100° F. is expected. Each expansion joint is to be 5 times as long as the maximum amount of lineal expansion occurring in each 100-ft. section of the pavement. What should be the length of each joint? How much will the surface area of a 100-ft. strip of pavement be increased by the expansion due to the anticipated range of temperature?

7. A concrete beam, reinforced with steel rods, is subjected to a bending load. A compressive stress is thus set up in one side of the beam while a tensile stress is set up in the opposite side. The tension is taken by the reinforcing rods. The coefficient of elasticity of the steel is 28,000,000 lb. per sq. in. If the rods are strained 0.000,1 in. per ft., what is the stress in them?

8. A bar of material is 0.3 sq. in. in cross-section and is 10 in. long. It elongates 0.002 in. when a load of 1,500 lb. is applied. Find the coefficient of elasticity.

9. A steel column is 12 sq. in. in cross-section and is 16 in. long. It supports a load of 200,000 lb. How much is it compressed?

10. A line of steam pipe is 375 ft. long. Steel pipe having a coefficient of expansion of 0.000,006,3 is used. The cross-sectional area of the pipe is 2.5 sq. in. How much will the line expand under a temperature increase of 350° F.? If the line were so secured that it could neither stretch nor buckle under the increase of temperature, what force would be set up in it?

11. What is the amount of lineal expansion in a set of steel boiler tubes, 20 ft. long, when their temperature is raised from 50° F. to 600° F.? The area of cross-section of each tube is 1 sq. in. If cold water could be run into one of the tubes, thus cooling it to 200° F. while it is held rigidly at both ends and while the others remain at 600° F., what would be the probable stress set up in the cooled tube?

12. A hot-water heating system contains 500 gal. of water. The coefficient of expansion of water is 0.000,1. The water is heated from 50° F. to 210° F. If the boiler, pipes, and radiators of the system do not expand, what quantity of water will rise into the expansion tank?

DIVISION 8

HEAT PHENOMENA OF GASES

224. Heat Phenomena Of Gases (see note below) are of great practical importance because of their application to the various heat engines and heat processes with which the engineer must deal. While the laws, which will be given and explained in this division, will not in all cases apply directly to actual heat engines, the fundamental ideas which underlie them do apply. Hence, an understanding of these laws is essential. Before proceeding, however, the reader should review the matter in Secs. 96 to 108 on the molecular theory of gases.

225. A Gas Is Any Substance In The Gaseous State Which Closely Follows The General Gas Law.—The general gas law is stated and explained in following Sec. 249; for the present it need not be further considered. All gaseous substances as they depart further from the temperature and pressure conditions necessary to effect their liquefaction obey more closely this general gas law. Gaseous substances which are at or near their liquefaction conditions are called vapors and do not even approximately obey this general gas law. Hence it is apparent that it is the degree of departure of the conditions, under which a gaseous-state substance is existing, from its liquid-state conditions that determines whether it is a gas or a vapor. See note below.

NOTE.—THE DISTINCTION BETWEEN A GAS AND A VAPOR IS ONE OF DEGREE.—The early scientists gave the name "permanent gas" to such gaseous substances as they believed could not be liquefied—as, for example, air, hydrogen, oxygen, and nitrogen. More recent investigations have shown, however, that all of these substances can be liquefied when cooled to very low temperatures. Such substances, as water and ammonia, which need not be cooled to very low temperature, to be liquefied, were, by the earlier scientists, called vapors when in the gaseous state. These terms—"vapor" and "gas"—have been preserved. but their modern meanings are quite different from theirformer meanings.

Any substance, at least theoretically, may exist (in the gaseous state) as either a vapor or a gas. Vapors are further discussed in Div. 11. Since it is really the "nearness" of a gaseous substance to the liquid state that determines whether it is a vapor or a gas, it is obvious that there cannot be any rigid line of demarcation between the two. The transition from the vapor form to the gas form, or vice versa is not abrupt—it is gradual.

A vapor has been defined by some physicists as a substance in its gaseous state below its certical temperature (Sec. 349); and a gas as a substance in its gaseous state above its certical temperature. But these definitions are not, apparently, in accord with those of the best modern authorities.

226. The Laws Which Will Be Treated In This Division Apply With Absolute Accuracy Only To A Hypothetical "Perfect" Or "Ideal" Gas.—A *perfect gas* is one which, when heated or cooled, absorbs or gives up no disgregation heat (Sec. 258). No gas, so investigation shows, is, in this sense, a perfect gas. But many gases (air, oxygen, hydrogen, nitrogen and the like) are so nearly "perfect" that the errors, which will result from considering them as perfect in engineering computations, will be inconsequential. *Vapors* (Div. 11) on the other hand (such as slightly superheated or saturated steam, ammonia, carbon dioxide and sulphur dioxide) have characteristic properties such that the perfect-gas laws do not apply accurately to them.

Note.—In Dealing With Vapors, it is ordinarily necessary to use values which are taken from tables, as for example Steam Table 394. Such values are experimentally-determined ones. Steam and other vapors are treated in Div. 11.

227. The "Condition" Of a Gas—this is a technical term which is difficult to define—is determined by: (1) *The kind of gas;* that is, its chemical composition. (2) *The weight of the gas.* (3) *Its pressure.* (4) *Its volume.* (5) *Its temperature.* As will be shown, for a given gas, any three of the last four of the above items determine the unknown properties. Whenever any of these properties of a gas are altered, the gas is said to undergo a *change in condition or a condition change.* It will be shown in this division, how changes in one or more of the above properties of a gas affect its remaining properties. It will also be shown how condition changes are affected by heat transfer and external work.

EXAMPLE.—If a quantity of a gas (Sec. 225) such as air, hydrogen or nitrogen is compressed (Fig. 214) in a closed vessel, its volume will (as the impressed pressure is increased) readily decrease (Fig. 215), in

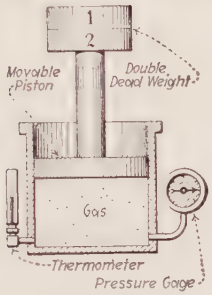


FIG. 214.—Illustrating the compression of a gas. As the weights 1 and 2 are placed on the rod, the gas is compressed.

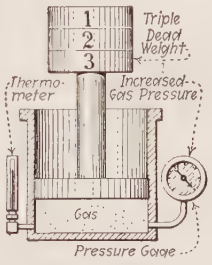


FIG. 215.—Illustrating the effect of increased compression due to addition of third weight.

proportion to the applied pressure. Or, if the pressure is decreased (Fig. 216), the body of gas will expand correspondingly and fill the larger space. In compressing the gas (Fig. 215), the falling weight does external work on it. All of this work (assuming a frictionless piston and no loss of heat) is converted into heat in the compressed gas. Thereby the temperature of the gas is increased. When the gas is permitted to

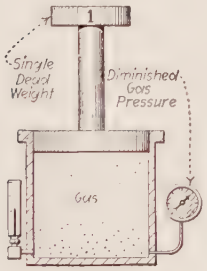


FIG. 216.—Illustrating the effect of diminished compression due to removing weight.

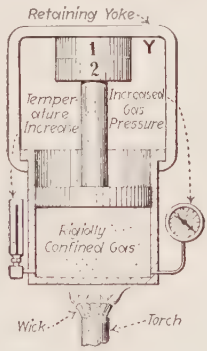


FIG. 217.—Illustrating increase of pressure by heating. (Compare with Fig. 214.)

expand (Fig. 216), it does work in raising the weight. Its heat content and temperature are thereby decreased accordingly.

Now, if heat be applied to the vessel (Fig. 217) and the piston is restrained by yoke, *Y*, from upward movement, the pressure exerted by the gas will increase. The added heat (energy) causes an increase in

the molecular vibration (Sec. 52) which produces the increased pressure. If (Fig. 218) there is no restraining yoke, the pressure of the gas must, as it is heated, remain constant (until P is pushed from the cylinder) but the volume of the gas will increase: Obviously, heat energy derived from the torch flame (Fig. 218) is converted into mechanical energy which does work in raising the weights.

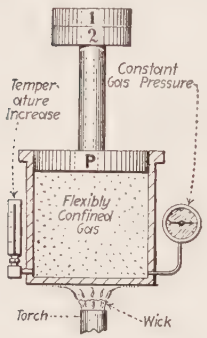


FIG. 218.—Illustrating increase of volume by heating. (Compare with Fig. 214.)

The above-described—and other—gas-condition changes occur in conformity with certain definite laws. It is proposed to consider these laws in succeeding sections.

228. Physical Gas Phenomena Will First Be Considered Without Reference To Energy Or Work Transfer Or Changes. That is, before proceeding with the energy relations for gas expansion and contraction, the following laws and subjects will be discussed: (1) *Boyle's law*, Sec. 230. (2) *Charles' law*, Sec. 237. (3) *Gay-Lussac's law*, Sec. 240. (4) *General gas law*, Sec. 248. (5) *Gas densities*, Sec. 253. (6) *Draft produced by differences in gas density*, Sec. 256. It is desirable that these laws and subjects be thoroughly understood before the reader studies the energy and work relations which apply in the expansion and contraction of gases.

229. Certain Laws Which Follow Relate To Changes Wherein Some Property Such As Temperature, Volume Or Pressure Remains "Constant."—This does not mean that necessarily the property must actually remain the same during the whole while that the change is occurring in order that the law may apply. The laws will apply not only when the "constant" condition is not varied while the change is occurring but they will also apply when after a change, the "constant" property is restored to its original value.

EXAMPLE.—Boyle's law which follows applies only when the gas temperature is maintained "constant." But the law is effective in computing the volume or pressure for a second condition if the volume and pressure for the first condition are known, provided the gas temperature for the second condition is restored to its original value, although gas temperature changes may have occurred in the meantime.

230. Boyle's Law, first stated by the Irish physicist, Robert Boyle, who discovered it experimentally, is: *If the temperature*

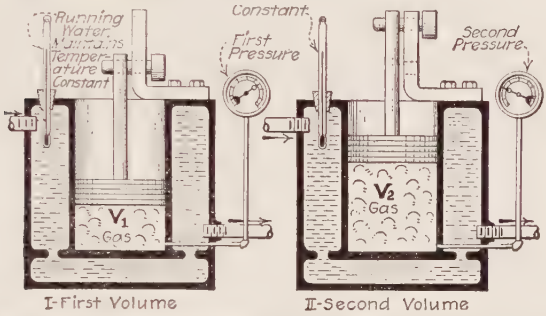


FIG. 219.—Boyle's law—temperature of a given weight of gas kept constant—pressure varies inversely as the volume. (Running water maintains gas temperature constant.) The pin holds the piston in fixed positions. In *II* the volume is twice that of *I*; hence the pressure in *II* is ½ that in *I*.

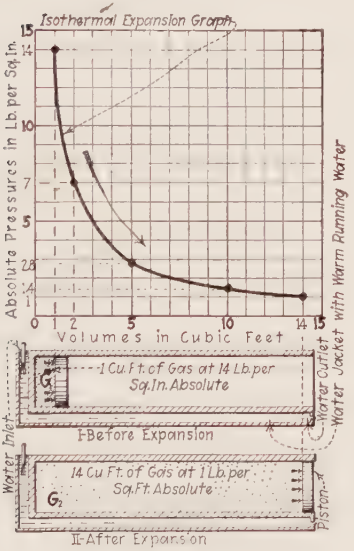

Isothermal Expansion Graph
Absolute Pressures in Lb. per Sq. In.
Volumes in Cubic Feet
1 Cu. Ft. of Gas at 14 Lb. per Sq. In. Absolute
I-Before Expansion
14 Cu. Ft. of Gas at 1 Lb. per Sq. In. Absolute
II-After Expansion
Water Inlet
Water Outlet
Water Jacket with Warm Running Water
Piston

FIG. 220.—Gas expansion in accordance with Boyle's law. (Temperature maintained constant through heating effect of water jacket.)

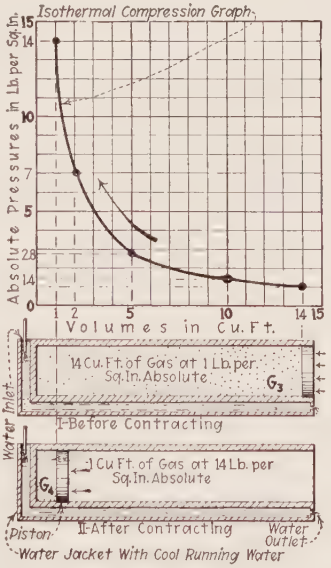

Isothermal Compression Graph
Absolute Pressures in Lb. per Sq. In.
Volumes in Cu. Ft.
14 Cu. Ft. of Gas at 1 Lb. per Sq. In. Absolute
I-Before Contracting
1 Cu. Ft. of Gas at 14 Lb. per Sq. In. Absolute
II-After Contracting
Water Inlet
Water Outlet
Piston
Water Jacket With Cool Running Water

FIG. 221.—Gas compression in accordance with Boyle's law. (Constant temperature maintained through cooling effect of jacket-water.)

of a given weight of gas is kept constant (Fig. 219), *the absolute pressure of the gas will vary inversely as its volume;* conversely,

the volume will vary inversely as the absolute pressure. Note particularly that this law applies only when the gas temperature is maintained constant (see Sec. 229). That is, it applies only for *isothermal* (constant temperature) *changes* (Sec. 271). The law means (Figs. 220 and 221) that with a given weight of gas, if the volume of the gas is doubled, its absolute pressure will be halved, if its volume is tripled, its absolute pressure will then be one third of the original pressure, and so on.

231. The Problems To Which Boyle's Law May Be Applied are those wherein the *volume* of a *given weight* of a gas at a *certain pressure* is known and it is desired to compute the *volume* of the gas at a different *pressure,* or the *pressure* exerted by the gas when it occupies a different *volume,* the gas *temperature being the same* for the second condition as for the first. In practice, it is regarded more convenient by some persons to apply the general gas law of For. (145) for the solution of these problems.

232. The Boyle's-law Formula, which follows directly from the verbal statement of the law, is:

$$\frac{P_1}{P_2} = \frac{V_2}{V_1} \qquad \text{(ratio)} \tag{108}$$

Wherein: P_1 and P_2 = respectively, the initial and final absolute pressures of any given weight of gas at a constant temperature (Sec. 229) in any pressure unit whatsoever, but both must be in the same unit. V_1 and V_2 = respectively, the initial and final volumes of the gas, in any volume unit whatsoever, but both must be in the same unit.

Note.—It Is Important To Note That In Any Problem Which Involves Initial And Final Conditions Of Gases, Either Condition May Be Considered The Initial And Either The Final Condition.—Thus, in applying Boyle's law, if there is a known value for P_2, and P_1 is desired, then P_2 may be considered the initial and P_1 the final pressure. The same numeral subscript always refers to one set of conditions existing at the same time and must not be confused. That is, P_2 always refers to the pressure at a volume of V_2 and a temperature (see following sections) of T_2. All the gas changes considered in this division, however, are reversible (Sec. 154) and may be thought of as taking place in either direction.

Note.—Transposed Forms Of Boyle's Law, which are useful in solving problems, are here given:

$$P_2 = \frac{P_1 V_1}{V_2} \qquad \text{(final absolute pressure)} \tag{109}$$

$$V_2 = \frac{P_1 V_1}{P_2} \qquad \text{(final volume)} \tag{110}$$

Wherein all symbols have the same meanings as stated under For. (108).

Example.—A certain weight of gas is compressed into a steel cylinder of a volume of 0.2 cu. ft. (V_1, Fig. 222) and then exerts a pressure of 200 lb. per sq. in. gage. What will be the volume of this gas at atmospheric pressure (0 lb. per sq. in. gage) when the temperature in V_2 is the original temperature in V_1? Solution.—By For. (110), $V_2 = P_1V_1/P_2 = (200 + 14.7) \times 0.2 \div (0 + 14.7) = 2.92$ *cu. ft.*

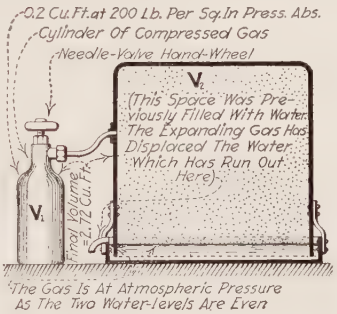

0.2 Cu.Ft.at 200 Lb. Per Sq.In Press. Abs.
Cylinder Of Compressed Gas
Needle-Valve Hand-Wheel
V2
(This Space Was Previously Filled With Water. The Expanding Gas Has Displaced The Water Which Has Run Out Here)
V1
Initial Volume = 0.2 Cu.Ft.
The Gas Is At Atmospheric Pressure As The Two Water-levels Are Even

Fig. 222.—Certain weight of a gas, compressed to a volume, V_1, of 0.2 cu. ft. at 200 lb. per sq. in. gage pressure. What will be its volume, V_2, at atmospheric pressure? Temperature remains constant.

Example.—A certain gas container has in it 54,300 cu. ft. of a gas when the barometer registers 29.12 in. of mercury column. Only atmospheric pressure is imposed on the gas in the container. Without leakage and without temperature change, it is found that the volume of the gas in the container increases to 54,650 cu. ft. What is the barometric pressure for the larger volume? Solution.—Barometers measure absolute pressures. Substitute in For. (109): $P_2 = P_1V_1/V_2 = 29.12 \times 54{,}300 \div 54{,}650 = 28.93$ *in. mercury column.*

233. For A Given Weight Of Gas At A Constant Temperature, The Product Of The Absolute Pressure And The Volume Will Be Constant regardless of the pressure and corresponding volume and vice versa. This is therefore the governing relationship for isothermal changes (Sec. 271). This is merely another statement of *Boyle's law* because by transposing For. (108), there results:

$$P_1V_1 = P_2V_2 = P_3V_3 \text{ etc} \qquad \text{(a constant)} \tag{111}$$

or this may be written:

$$PV = k \qquad \text{(a constant)} \tag{112}$$

Explanation.—A cylinder (Fig. 223) with a movable piston head, P, contains 2 cu. ft. of gas at an absolute pressure of 30 lb. per sq. in.

For this condition, *pressure* × *volume* = $PV = 30 \times 2 = 60$. Now weights, W (Fig. 224), are added to the movable head until the volume of the gas is compressed to 1 cu. ft. (The cylinder is so surrounded with running water that it carries away the heat generated by the compression and maintains the temperature of G constant.) By the addition of the

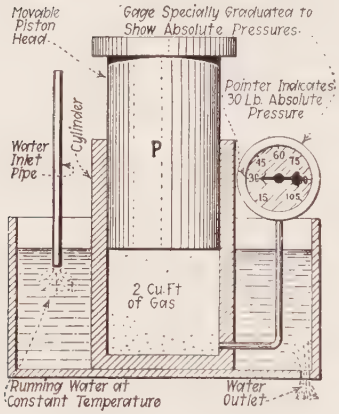


Fig. 223.—Illustrating Boyle's law, 2 cu. ft., at 30 lb. per sq. in. abs. pressure.

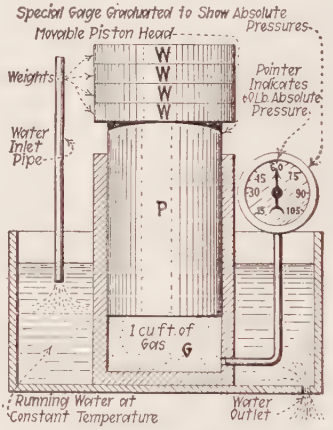


Fig. 224.—Illustrating Boyle's law, 1 cu. ft. at 6 lb. per sq. in. abs. pressure.

weights the pressure will be increased to (For. 109) 60 lb. per sq. in. abs. But $PV = 1 \times 60 = 60$ as before. For any other pressure and volume, their product would be 60. Furthermore, it will be noted from Figs. 220 and 221, that the product of P and V for any point on either of these Boyle's-law graphs is a constant. Thus: $14 \times 1 = 14$; $7 \times 2 = 14$; $2.8 \times 5 = 14$; $1.4 \times 10 = 14$; $1 \times 14 = 14$. It obviously follows then that:

(113) $$P_1V_1 = P_2V_2 = P_3V_3 \ldots\ldots\ldots\ldots, \text{etc.} = k \quad \text{(a constant)}$$

which is the statement of For. (112) above.

234. The Pressure-temperature Changes At Constant Volume for a given weight of any certain gas were early investigated (see note under Sec. 237) and found to follow a general law (to be here called Charles' law): *If a given weight of any gas is confined in a fixed volume and its pressure is measured while the gas is at 32° F., it will be found that its absolute pressure will increase $\frac{1}{492}$ for each 1° F. that its temperature is increased* —or, *its absolute pressure will decrease $\frac{1}{492}$ for each 1° F.*

that its temperature is decreased. This relation may be written as a formula, thus:

(114) $P_T = P_{32}[1 + \frac{1}{492}(T - 32)]$ (abs. pressure)

or, expressing "$\frac{1}{492}$" as a decimal:

(115) $P_T = P_{32}[1 + 0.002{,}033\ (T - 32)]$ (abs. pressure)

Wherein: P_T = the absolute pressure of a gas, in any unit of pressure, at a certain temperature, T, and in a certain volume V. P_{32} = the absolute pressure of the same gas, in the same units as P_T is measured, when in the same volume, V, and at 32° F. T = the temperature of the gas when exerting the pressure, P_T, in degrees Fahrenheit.

Example.—A certain weight of gas, when confined in a closed container at 32° F., exerts a pressure of 100 lb. per sq. in. abs. Now at 33° F. and in the same volume, its pressure will be $\frac{1}{492} \times 100 = 0.203{,}3$ lb. per sq. in. greater than at 32° F. Furthermore, at 42° F. its pressure will be $10 \times 0.203{,}3 = 2.033$ lb. per sq. in. greater than at 32° F. These same results may have been found by using For. (115), thus: At 33° F., $P_T = P_{32}[1 + 0.002{,}033(T - 32)] = 100[1 + 0.002{,}033(33 - 32)] = 100(1 + 0.002{,}033) = 100.203{,}3$ *lb. per sq. in. abs.* Likewise at 42° F., $P_T = 100[1 + 0.002{,}033(42 - 32)] = 100(1 + 0.020{,}33) = 102.033$ *lb. per sq. in. abs.*

Example.—A cubic foot of air at 32° F. is under pressure of 300 lb. per sq. in. abs. What would be the pressure if the air were cooled in the same volume to 0° F.? Solution.—By For. (115), $P_T = P_{32}[1 + 0.002{,}033(T - 32) = 300[1 + 0.002{,}033(0 - 32)] = 300\ (1 - 0.065) = 280.5$ *lb. per sq. in. abs.*

235. The Volume-temperature Changes At Constant Pressure for a given weight of any gas were also investigated (see note under Sec. 237) and found to follow a similar law to that given in the preceding section. The law governing the volume-temperature changes at constant pressure for a given weight of a gas is to be here called Gay Lussac's law: *If a given weight of any gas be so confined that its volume and temperature can be varied while its pressure remains constant, it is found that the volume increases $\frac{1}{492}$ of the volume at 32° F. for each 1° F. increase in its temperature; likewise the volume of the gas decreases $\frac{1}{492}$ of its volume at 32° F. for every 1° F. decrease in temperature.* This relation may be written as a formula, thus:

(116) $V_T = V_{32}[1 + \frac{1}{492}(T - 32)]$ (volume)

or, expressing "1/492" as a decimal:

(117) $$V_T = V_{32}[1 + 0.002{,}033(T - 32)] \qquad \text{(volume)}$$

Wherein: V_T = the volume of a given weight of gas (in any unit) at a certain temperature, T, and pressure P. V_{32} = the volume of the same gas when at 32° F. and under the same pressure P. T = the temperature, in degrees Fahrenheit, at which the gas occupies the volume V_T.

Example.—If at 32° F. and at atmospheric pressure a certain weight of a gas occupies 2 cu. ft., what volume will that same gas occupy at 50° F., at 800° F., and at −20° F., the pressure being in each case that of the atmosphere? Solution.—By For. (117), $V_T = V_{32}[1 + 0.002{,}033(T - 32)]$. Hence, at 50° F., $V_T = 2[1 + 0.002{,}033(50 - 32)] = 2(1 + 0.036{,}6) = 2.073{,}2$ *cu. ft.* At 800° F., $V_T = 2[1 + 0.002{,}033(800 - 32)] = 2(1 + 1.561) = 5.132$ *cu. ft.* At −20° F., $V_T = 2[1 + 0.002{,}033(-20 - 32)] = 2(1 - 0.105{,}7) = 1.788{,}6$ *cu. ft.*

236. Our Notion Or Concept Of Absolute Temperature is based on the laws of Charles and Gay Lussac, as given in Secs. 234 and 235. If an attempt is made, by using For. (114), to find the pressure exerted by any gas at the temperature of −460° F., it is evident that the resulting pressure is zero. Likewise, cooling a gas at constant pressure to −460° F., will, by For. (116), reduce its volume to zero. Hence, if any (perfect) gas followed these laws exactly and if it were possible to cool the gas gradually to a lower and lower temperature, it would be found that, at −460° F., the gas would occupy no volume and would exert no pressure on the wall of its containing vessel. Therefore, it is logical to assume that no lower temperature than −460° F. can ever be attained for, if a lower temperature could be attained, then the volume of a gas would, by For. (116), become negative—which is inconceivable. Hence, −460 F. is called the *absolute zero of temperature* and temperatures measured from −460° F. as a starting or datum point are called *absolute temperature* (see also Sec. 61). As a formula:

(118) $$\mathbf{T} = T + 460 \qquad \text{(deg. fahr. abs.)}$$

or, transposing:

(119) $$T = \mathbf{T} - 460 \qquad \text{(deg. fahr.)}$$

Wherein: T = the temperature of any body, in degrees

Fahrenheit on the *absolute scale*. T = the temperature of the body in degrees Fahrenheit on the *Fahrenheit scale*.

EXAMPLE.—See examples under Sec. 62.

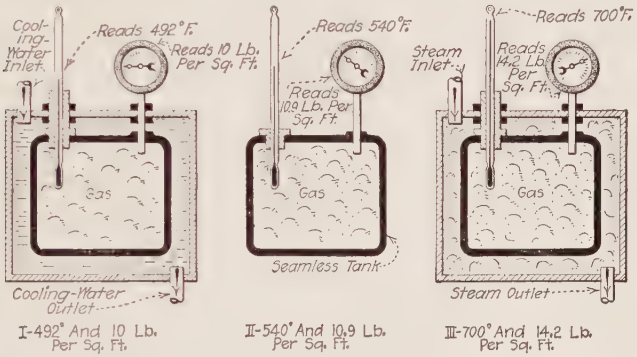


FIG. 225.—Illustrating Charles' law. With a constant volume of a given weight of gas, the absolute pressure varies as the absolute temperature. (See following graph for points corresponding to *I*, *II*, and *III* above.)

237. Charles' Law may be stated thus: *If the volume of a given weight of gas* (Fig. 225) *is kept constant, the absolute pressure will vary directly as the absolute temperature of the gas.* Note particularly that this law applies only when the volume of the gas is maintained constant (see Sec. 229). That is, it applies only for *isometric* (constant volume) *changes* (Sec. 269). This law means that, with the volume held constant, if the absolute temperature of a given weight of a gas is doubled, its absolute pressure will be doubled; if its absolute temperature is tripled, its absolute pressure will be tripled and so on. Likewise, halving the absolute temperature halves the pressure, etc. Figure 226 illustrates this

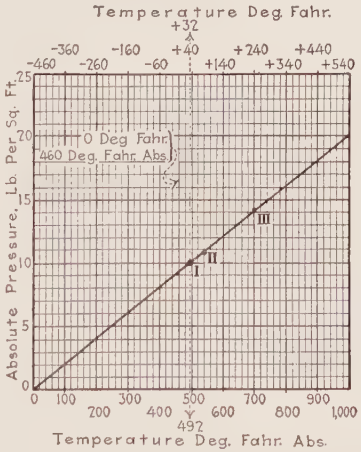


FIG. 226.—Graph illustrating Charles' law. Shows variations of pressure with temperature, of any given weight of a perfect gas, which is maintained at constant volume and which exerts a pressure of 10 lb. per sq. ft. at 32° F.

fact graphically. See Sec. 239 for proof that the above statements are the same as those of Sec. 234.

Note.—Charles' Law As Just Above Stated Is Also Sometimes Called Dalton's Law or Gay Lussac's Law. (This should not be confused with Dalton's laws of mixed-gas partial pressures Sec. 306, which is an entirely different thing.) "Dalton in 1801 first published the law. Gay Lussac, independently of Dalton, published the law in 1802. In his publication, Gay Lussac states that Charles in 1787 had noted the law but had never published it." (Stone's Experimental Physics, p. 92, *Ginn & Co.*, 1897). The above "Charles' law" and the following "Gay Lussac's law" are together often referred to variously by different writers as either Charles' law or Gay Lussac's law. But for the purposes of this book, it is deemed wiser to adopt the nomenclature which is indicated.

238. The Problems To Which Charles' Law May Be Applied are those wherein the pressure of a given weight of gas, which is maintained at a constant volume, is known for a certain temperature and it is desired to compute either the pressure exerted by the gas at a different temperature or the temperature necessary to produce a different pressure. In practice, it is regarded as more convenient, by some people, to apply the *general gas law*, For. (145), for solving these problems.

Note.—The Only Changes To Which Charles' Law Applies Are Those Which Are Caused By The Addition Or Subtraction Of Heat, whereby the gas temperature is varied. The law cannot, since it is true only for *a given weight of gas at constant volume*, hold for changes caused by adding or subtracting gas or by compressing or expanding it.

239. The Charles'-law Formula which expresses the relationship as given in the statement of the law (Sec. 237) is:

$$\frac{P_1}{P_2} = \frac{\mathbf{T}_1}{\mathbf{T}_2} \qquad \text{(ratio)} \tag{120}$$

or,

$$P_2 = \frac{P_1 \mathbf{T}_2}{\mathbf{T}_1} \qquad \text{(final pressure)} \tag{121}$$

or,

$$\mathbf{T}_2 = \frac{\mathbf{T}_1 P_2}{P_1} \qquad \text{(final temperature)} \tag{122}$$

Wherein: P_1 and P_2 = respectively the initial and final absolute pressures of any given weight of gas at constant volume, which may be expressed in any pressure unit but both must

be expressed in the same unit. $\mathbf{T}_1$ and $\mathbf{T}_2$ = respectively the initial and final absolute temperatures of the gas expressed in any temperature unit provided both are expressed in the same unit.

Derivation.—By For. (114): $P_T = P_{32}[1 + \frac{1}{492}(T - 32)]$. By For. (119): $T = \mathbf{T} - 460$. Now, substituting for T in For. (114), there results:

$$P_T = P_{32}\left\{1 + \frac{1}{492}\left[(\mathbf{T} - 460) - 32\right]\right\} \tag{123}$$

Simplifying, there results:

$$P_T = P_{32}\left[1 + \frac{1}{492}(\mathbf{T} - 492)\right] \tag{124}$$

$$P_T = P_{32}\left[1 + \frac{\mathbf{T}}{492} - \frac{492}{492}\right] \tag{125}$$

$$P_T = P_{32}\left[1 + \frac{\mathbf{T}}{492} - 1\right] \tag{126}$$

$$P_T = P_{32} \times \frac{\mathbf{T}}{492} \tag{127}$$

$$\frac{P_T}{P_{32}} = \frac{\mathbf{T}}{492} \tag{128}$$

Now, 32° F. = 492° F. abs. Hence, by using the symbols of For. (120), For. (128) becomes:

$$\frac{P_1}{P_2} = \frac{\mathbf{T}_1}{\mathbf{T}_2} \tag{129}$$

which is the same as For. (120).

Example.—If the pressure of a certain weight of gas, the volume of which is maintained const nt, is 100 lb. per sq. in. absolute and its temperature is 300° F. abs., what increase in temperature is necessary to increase the pressure exerted by this weight of gas to 150 lb. per sq. in. abs.? Solution.—By For. (122), $\mathbf{T}_2 = \mathbf{T}_1 P_2/P_1 = 300 \times 150 \div 100 = 450°$ *F. abs.* This represents a temperature increase of $450 - 300 = 150°$ *F.*

Example.—The gage on an airtight compressed-air tank (constant volume) registers 115 lb. per sq. in. The air in it has been heated by compression to 150° F. What will the gage register when the air cools down to 70° F.? Solution.—By For. (121), $P_2 = P_1\mathbf{T}_2/\mathbf{T}_1 = (115 + 14.7) \times (70 + 460) \div (150 + 460) = 112.7$ *lb. per sq. in. abs.;* or $112.7 - 14.7 = 98.0$ *lb. per sq. in. gage.*

Example.—Say that 200 lb. per sq. in. is considered a safe gage pressure for a certain gas-storage tank (constant volume). Gas is pumped into the tank at a temperature of 49° F. until the pressure in the tank is 175 lb. per sq. in. gage. If the valves are all closed when the tank is full of gas in this condition, what will be the highest safe temperature to which the tank may be subjected? Solution.—By

For. (122), $T_2 = T_1P_2/P_1 = (49 + 460) \times (200 + 14.7) \div (175 + 14.7) = 576°$ *F. abs.*; or $576 - 460 = 116°$ *F.*

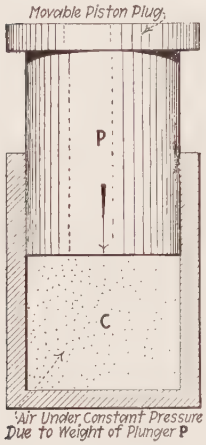


Fig. 227.—Air confined under constant pressure. (Since the weight of the perfectly-fitting frictionless piston plug and that of atmospheric pressure if any, are constant, the pressure imposed on and hence exerted by the air must be constant.)

240. Gay Lussac's Law may be stated thus: (Fig. 227): *If the absolute pressure of (imposed on) a given weight of any gas is kept constant, its volume will vary directly as the absolute temperature of the gas.* Note the similarity between this and Charles' law of Sec. 237; with Charles' law the volume is kept constant and the pressure varies while with Gay Lussac's law the pressure is kept constant and the volume varies. Also note particularly that *Gay Lussac's law applies only* when the pressure of, that is the pressure imposed on, the gas is maintained constant. That is, Gay Lussac's law applies only for *isobaric* (constant-pressure) *changes* (Sec. 270). This law means (Figs. 228 and 229) that, with the pressure held constant, if the absolute temperature of a given weight of gas is doubled, its volume will be doubled; if its absolute temperature is tripled, its volume will be tripled and so on.

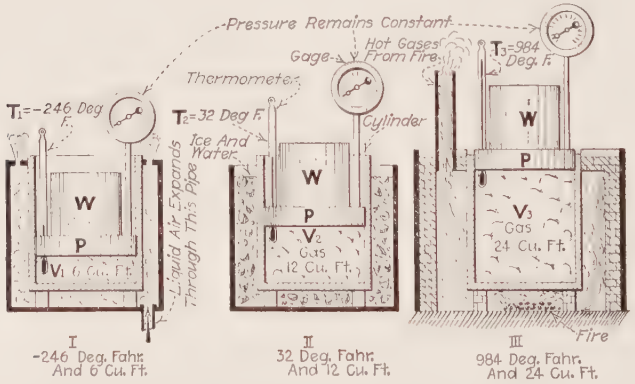


Fig. 228.—Diagram illustrating Gay Lussac's law. (With a given weight of gas at constant pressure, the volume varies as the absolute temperature. See following graph for points corresponding to *I*, *II*, and *III*, above.)

Likewise, halving the absolute temperature halves the volume; with $\frac{1}{3}$ the original absolute temperature the volume will be $\frac{1}{3}$ of the original volume, etc.

241. The Problems To Which Gay Lussac's Law May Be Applied are those wherein the volume of a given weight of gas, which is maintained at a constant pressure is known for a certain temperature and it is desired to compute either the volume of the gas at a different temperature or the temperature necessary to produce a different volume. Note that, in practice, it is usually more convenient to apply the *general gas law*, For. (145) for solving these problems.

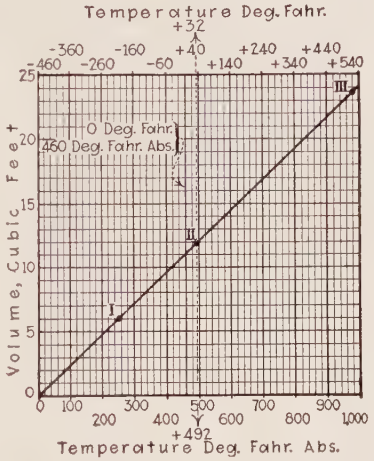


Fig. 229.—Graph illustrates Gay Lussac's law. Shows variation of volume directly with temperature, of any given weight of a perfect gas which is maintained at constant pressure and which occupies a volume of 12 cu. ft. at 32° F.

Note.—The Only Changes To Which Gay Lussac's Law Applies Are Those Which Are Caused By The Addition Or Subtraction Of Heat, whereby the gas temperature is varied. The law cannot, since it is true only for *a given weight of gas at constant pressure*, hold for changes caused by adding or subtracting gas or for changes by compressing or expanding it mechanically unless heat is simultaneously abstracted or added at just the proper rates to maintain the pressure constant.

242. The Gay Lussac's-law Formula, which expresses mathematically the preceding verbal statement of the law, is:

$$\frac{V_1}{V_2} = \frac{\mathbf{T}_1}{\mathbf{T}_2} \qquad \text{(ratio)} \tag{130}$$

or,

$$V_2 = \frac{V_1 \mathbf{T}_2}{\mathbf{T}_1} \qquad \text{(final volume)} \tag{131}$$

or,

$$\mathbf{T}_2 = \frac{\mathbf{T}_1 V_2}{V_1} \qquad \text{(final temp.)} \tag{132}$$

Wherein: V_1 and V_2 = respectively the initial and the final volumes of the gas which may be expressed in any unit of volume, but both must be expressed in the same unit. $\mathbf{T}_1$ and $\mathbf{T}_2$ = respectively the initial and final absolute temperatures of the gas expressed in any temperature unit provided both are expressed in the same unit.

Derivation.—The formula given above (130), can be derived from For. (116) just as was For. (120) derived from For. (114) in Sec. 239.

Example.—A given weight of a gas is confined at atmospheric pressure and occupies 75 cu. ft. at 520° F. abs. What volume will it occupy at 635° F. abs. and at the same pressure? Solution.—By For. (131), $V_2 = V_1\mathbf{T}_2/\mathbf{T}_1 = 75 \times 635 \div 520 = 91.6$ *cu. ft.*

Example.—A body of gas at 580° F. abs. is compressed to one third of its original volume. To what temperature must it be cooled to reduce its pressure to the same value as that before the compression? Solution.—By For. (132), $\mathbf{T}_2 = \mathbf{T}_1V_2/V_1 = 580 \times 1 \div 3 = 193°$ *F. abs.*

Example.—If a certain weight of a flexibly confined gas (Fig. 230), which is maintained at constant pressure has a volume of 9 cu. ft. at 32° F., what will be its volume when the gas is heated to 52°? What

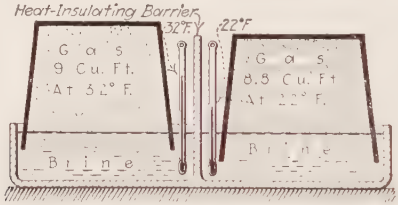


Fig. 230.—Showing decrease in volume at constant pressure due to 10° F. decrease in temperature.

would be its volume if the gas were cooled to 22° F.? Solution.—By For. (118), $\mathbf{T} = T + 460$. Hence $\mathbf{T}_1$, (32° F.) = 32 + 460 = 492° *F. abs.* Also, $\mathbf{T}_2$ (52° F.) = 52 + 460 = 512° *F. abs.* And, $\mathbf{T}_3$ (22° F.) = 22 + 460 = 482° *F. abs.* By For. (131), $V_2 = V_1\mathbf{T}_2/\mathbf{T}_1 = 9 \times 512 \div 492 = 9.37$ *cu. ft.* Also, $V_3 = V_1\mathbf{T}_3/\mathbf{T}_1 = 9 \times 482 \div 492 = 8.8$ *cu. ft.*

Example.—If 100 cu. ft. of air at 60° F. is drawn into a boiler furnace, what volume will this air occupy: (*a*) In the combustion chamber where the temperature is 2,350° F.? (*b*) In the last pass of the boiler where the temperature is 500° F.? (*c*) In the stack where the temperature is 250° F.? The pressure of the flue gases is, practically, atmospheric pressure in all parts of a furnace, boiler, and stack. Hence, the pressure may be assumed to be constant in this example.

Solution.—By For. (118), $\mathbf{T} = T + 460$. Hence, $\mathbf{T}_1$ (60° F.) = 60 + 460 = 520° *F.* abs. Also, $\mathbf{T}_2$ (2,350° F.) = 2,350 + 460 = 2,810° *F. abs.*

and T_3 (500° F.) = 500 + 460 = 960° *F. abs.* and T_4 (250° F.) = 250 + 460 = 710° *F. abs.* (*a*) By For. (131), $V_2 = V_1T_2/T_1 = 100 \times 2{,}810 \div 520 = 540$ *cu. ft.* (*b*) Also, $V_3 = V_1T_3/T_1 = 100 \times 960 \div 520 = 185$ *cu. ft.* (*c*) And, $V_4 = V_1T_4/T_1 = 100 \times 710 \div 520 = 137$ *cu. ft.*

243. A Combination Of Two Of The Three Fundamental Laws (Boyle's, Charles' And Gay Lussac's) May Be Employed To Determine The Effect Of Simultaneous Changes In Volume, Pressure, And Temperature, for a given weight of any gas, when values for all three of these properties are known for the initial condition and values for two of them are known for the final condition. (See Table 244.) *First,* to find the result due to the changes in two of the properties, one of the laws is employed. *Then,* one other of the laws is applied (using the value obtained in the first operation) to compute the effect of the change in the third property. In any case, the two formulas which are used are the ones in both of which the unknown quantity (V, P, or T) appears. The following example explains the operation.

Note.—For. (133) Which Combines In One Boyle's, Charles', And Gay Lussac's Laws, May Be Used Instead Of The Above Explained Operation.—Or, in practice, the general gas law, Sec. 249, which is usually more convenient and which is of broader application is, ordinarily, employed. The material in the preceding and following sections is included principally to permit of a logical development of the general gas law of following Sec. 249.

244. Table Showing Combined Applications Of Boyle's, Charles', And Gay Lussac's Laws.—See Sec. 243 (This applies only *for a given weight* of any gas).

GIVEN		TO FIND	Use these laws:	Formulas for the laws:
Initial	Final			
V_1 = Volume P_1 = Pressure $\mathbf{T}_1$ = Temperature	P_2 = Pressure $\mathbf{T}_2$ = Temperature	V_2 = Volume	Boyle's. Gay Lussac's.	$V_2' = \frac{V_1 P_1}{P_2}$, $V_2 = \frac{V_2' \mathbf{T}_2}{\mathbf{T}_1}$
	V_2 = Volume $\mathbf{T}_2$ = Temperature	P_2 = Pressure	Boyles'. Charles'.	$P_2' = \frac{V_1 P_1}{V_2}$, $P_2 = \frac{P_2' \mathbf{T}_2}{\mathbf{T}_1}$
	V_2 = Volume P_2 = Pressure	$\mathbf{T}_2$ = Temperature	Charles'. Gay Lussac's.	$\mathbf{T}_2' = \frac{\mathbf{T}_1 P_2}{P_1}$, $\mathbf{T}_2 = \frac{\mathbf{T}_2' V_2}{V_1}$

$\mathbf{T}$ = Absolute temperature in the above table.

Example.—A cylinder (Fig. 231) contains 1 cu. ft. of gas at an absolute pressure of 15 lb. per sq. in., and temperature of 500° F. abs. Now, the absolute pressure is increased (Fig. 232) to 30 lb. per sq. in. Then, the

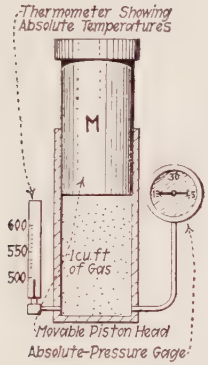


Fig. 231.—Illustrating the initial condition of the gas in the example.

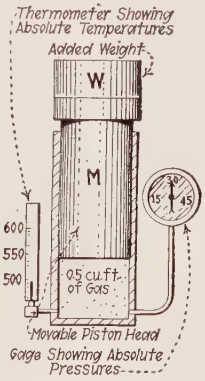


Fig. 232.—First change; change of volume and pressure in accordance with Boyle's law.

temperature is increased (Fig. 233) to 600° F. abs. What is the resulting volume? (The final result would be the same if the above-specified changes all occurred simultaneously instead of occurring one after the other.)

Solution.—Call the volume of the gas after the first change (Fig. 232) V_2'. Then, in accordance with Boyle's law, the final volume due to the pressure change alone, as given by For. (110) = $V_2' = P_1V_1/P_2 = 1 \times 15 \div 30 = 0.5$ *cu. ft.* Then according to Gay Lussac's law, the volume due to the temperature change alone, as given by For. (131) = $V_2 = V_2'T_2/T_1 = 0.5 \times 600 \div 500 = 0.6$ *cu. ft.*

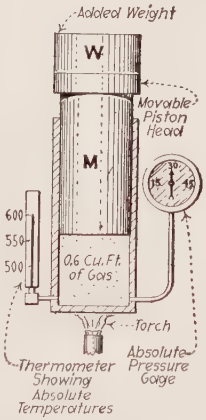


Fig. 233.—Second change; change of volume and temperature in accordance with Gay Lussac's law.

245. The Formula Which Combines Boyle's, Charles', And Gay Lussac's Laws and which applies for a given weight of any gas, the derivation of which is given below, is this:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \qquad \text{(units as noted)} \tag{133}$$

Or, by transposing,

$$P_2 = \frac{P_1 V_1 \mathbf{T}_2}{V_2 \mathbf{T}_1} \qquad \text{(final abs. pressure)} \tag{134}$$

$$V_2 = \frac{P_1 V_1 \mathbf{T}_2}{P_2 \mathbf{T}_1} \qquad \text{(final volume)} \tag{135}$$

$$\mathbf{T}_2 = \frac{P_2 V_2 \mathbf{T}_1}{P_1 V_1} \qquad \text{(final temperature)} \tag{136}$$

Wherein: P_1 and P_2 = respectively, the initial and final absolute pressures of the gas in any pressure unit but both must be in the same unit. V_1 and V_2 = respectively, the initial and final volumes of the gas in any volume unit but both must be in the same unit. $\mathbf{T}_1$ and $\mathbf{T}_2$ = respectively, the initial and final absolute temperatures of the gas both on the same scale.

Derivation.—Repeating the three fundamental gas-law formulas and stating them in their general forms without employing any specific units: Boyle's law, For. (108) is:

$$\frac{P_1}{P_2} = \frac{V_2}{V_1} \text{ or } P_1 V_1 = P_2 V_2 \tag{137}$$

Charles' law, For. (120) is:

$$\frac{P_1}{P_2} = \frac{\mathbf{T}_1}{\mathbf{T}_2} \text{ or } P_1 \mathbf{T}_2 = P_2 \mathbf{T}_1 \tag{138}$$

Gay Lussac's law, For. (130) is:

$$\frac{V_1}{V_2} = \frac{\mathbf{T}_1}{\mathbf{T}_2} \text{ or } V_1 \mathbf{T}_2 = V_2 \mathbf{T}_1 \tag{139}$$

Now multiplying together the second forms of each of the above equations, there results:

$$P_1 V_1 \times P_1 \mathbf{T}_2 \times V_1 \mathbf{T}_2 = P_2 V_2 \times P_2 \mathbf{T}_1 \times V_2 \mathbf{T}_1 \tag{140}$$

Or performing the multiplication indicated above:

$$P_1^2 V_1^2 \mathbf{T}_2^2 = P_2^2 V_2^2 \mathbf{T}_1^2 \tag{141}$$

Extracting the square root of both sides of the equation:

$$P_1 V_1 \mathbf{T}_2 = P_2 V_2 \mathbf{T}_1 \tag{142}$$

Or transposing to a more convenient form:

$$\frac{P_1 V_1}{\mathbf{T}_1} = \frac{P_2 V_2}{\mathbf{T}_2} \tag{143}$$

which is the same as For. (133).

Example.—Solve, using For. (133) transposed, the example which is given under Sec. 244. Solution.—By For. (135), $V_2 = P_1 V_1 \mathbf{T}_2 / P_2 \mathbf{T}_1 = 15 \times 1 \times 600 \div 500 \times 30 = 0.6$ *cu. ft.*

Example.—A certain quantity of air (Fig. 234) has a volume of 40 cu. ft. when at a pressure of 30 lb. per sq. in. abs. and a temperature of

80° F. The air is permitted to expand until its volume is 80 cu. ft. and simultaneously its temperature is reduced (by cooling) to 50° F. What is the absolute pressure which is exerted by the air at the end of its expansion? SOLUTION.—80° *F.* = 80 + 460 = 540° *F. abs.* 50° *F.* = 50 + 460 = 510° *F. abs.* Now, by For. (134), $P_2 = P_1V_1T_2/V_2T_1 = 30 \times 40 \times 510 \div 80 \times 540 = 14.2$ *lb. per sq. in. abs.*

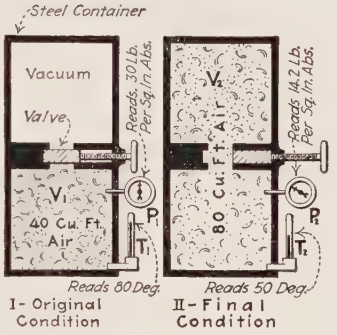


FIG. 234.—What is the final pressure, P_2, of the air?

EXAMPLE.—If a city is supplied with natural gas (Fig. 235) under an agreement to pay 25 ct. per 1,000 cu. ft. when the gas is measured at atmospheric pressure (14.7 lb. per sq. in. abs.) and at 60° F., what should the city pay for 20,000 cu. ft. measured at 90° F. and 300 lb. per sq. in. gage? SOLUTION.—Since this is a problem involving a given weight of a given gas, it may be solved by the combined gas law, Sec. 245. Applying For. (135), $V_2 = P_1V_1T_2/P_2T_1 = (300 + 14.7) \times 20{,}000 \times (460 + 60) \div [14.7 \times (460 + 90)] = 314.7 \times 20{,}000 \times 520 \div (14.7 \times 540) = 412{,}300$ *cu. ft* Hence, the city should pay \$0.25 × (412,300 ÷ 1,000) = \$103.08.

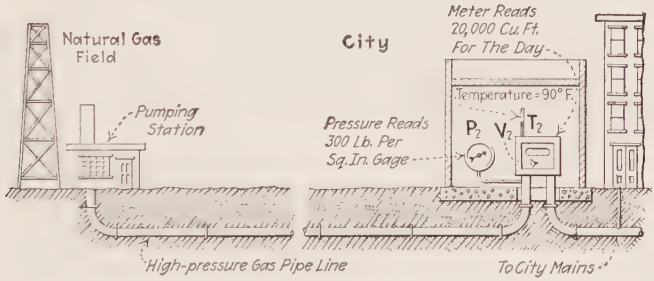

Natural Gas Field
Pumping Station
City
Meter Reads 20,000 Cu. Ft. For The Day
Temperature = 90° F.
Pressure Reads 300 Lb. Per Sq. In. Gage
P2 V2 T2
High-pressure Gas Pipe Line
To City Mains

FIG. 235.—At 25 ct. per 1,000 cu. ft. measured at 14.7 lb. per sq. in. abs. and at 60° F., how much does the city owe for the day's supply of gas?

NOTE.—TERMS USED IN THOSE HEAT-ENGINE PROBLEMS, WHICH MAY BE SOLVED BY APPLYING THE GENERAL GAS LAW FORMULAS, and which should be understood before proceeding, are: *The "bore" of an engine* is the internal diameter of its cylinder—the outside diameter of its piston. *The "stroke" of an engine* is the lineal distance, along the cylinder, which is swept through by the piston; it is equal to the travel of the crosshead. *The "clearance"* or *"clearance volume" of an engine* is the volume of space, in the engine cylinder, left between the adjacent cylinder head and the piston when the piston is at the end of its stroke,

plus the volume of the part which leads to it; clearance is usually expressed as a ratio in per cent thus: *Clearance* = (*clearance volume*)/(*volume swept through by piston*). *The "displacement volume" of an engine* is the volume through which the piston sweeps.

Example.—A gas engine, which has a clearance of 20 per cent., draws in a charge of gas at atmospheric pressure and at a temperature of 70° F. The charge completely fills the clearance and the displacement volumes. The charge is then, prior to ignition, compressed into the clearance. The gage pressure, which the gas then exerts, as shown by a pressure gage, is 145.3 lb. per sq. in.; what is the temperature of the gas?

Solution.—$\mathbf{T}_2$ = the unknown. $\mathbf{T}_1 = 70 + 460 = 530°$ *F. abs.* $P_1 = 14.7$ *lb. per sq. in. abs.* $P_2 = 145.3 + 14.7 = 160.0$ *lb. per sq. in. abs.* V_1 = (*displacement volume*) + (*clearance volume*) = 100 *per cent.* + 20 *per cent.* = 120 *per cent.* V_2 = *clearance volume* = 20 *per cent.* Now, substitute in For. (136): $\mathbf{T}_2 = P_2V_2\mathbf{T}_1/P_1V_1 = (530 \times 160 \times 20) \div (14.7 \times 120) = 1{,}696{,}000 \div 1{,}764 = 961°$ *F. abs.* or $961 - 460 = 501°$ *F.*

Example.—Assume that the charge of gas, after being compressed, as in the preceding example, is ignited. If the temperature—combustion temperature—then becomes 3,258° F. and the piston has not moved from the final position which was specified in the example just preceding, what then will be the pressure against the piston?

Solution.—Since the gas charge here considered is the same one that was used in the first gas-engine example, the same original, initial condition may be taken for the preceding example and for this example. Hence: $P_1 = 14.7$ *lb. per sq. in. abs.* P_2 = the unknown. $V_1 = 120$ *per cent.* $V_2 = 20$ *per cent.* $\mathbf{T}_1 = 530°$ *F. abs.* $\mathbf{T}_2 = 3{,}258 + 460 = 3{,}718°$ F. *abs.* Now, substitute in For. (134): $P_2 = P_1V_1\mathbf{T}_2/V_2\mathbf{T}_1 = (14.7 \times 120 \times 3{,}718) \div (20 \times 530) = 6{,}558{,}552 \div 10{,}600 = 618.7$ *lb. per sq. in. abs.* Another Solution Of This Same Example could be effected by using in this example the final-condition values from the preceding example, thus: $P_2 = P_1V_1\mathbf{T}_2/V_2\mathbf{T}_1 = (160 \times V \times 3{,}718) \div (V \times 961) = 594{,}880 \div 961 = 618.7$ *lb. per sq. in. abs.* or $618.7 - 14.7 = 604$ *lb. per sq. in. gage.*

Example.—The same charge of gas, which was considered in the two examples just preceding, was ignited and exploded in the previous example. It now expands and pushes the gas-engine piston before it to the end of the expansion stroke. If the pressure exerted by the gas at the end of its expansion stroke is 40 lb. per sq. in. abs., what is its temperature?

Solution.—Since the gas charge which is considered here is the same one that was used in the first gas-engine example, the same original, initial conditions which were employed in the two examples just preceding may be used in this example. Hence: $\mathbf{T}_2$ = the unknown. $\mathbf{T}_1 = 530°$ *F. abs.*, from the preceding example. $P_1 = 14.7$ *lb. per sq. in. abs.* $P_2 = 40$ *lb. per sq. in. abs.* V remains constant, since for both the second and the first conditions it is 120 per cent. Now substitute in For. (136): $\mathbf{T}_2 = P_2V_2\mathbf{T}_1/P_1V_1 = (530 \times 40 \times V) \div (14.7 \times V) = 21{,}200 \div 14.7 =$

1,442° *F. abs.* Another Solution Of This Same Example could be effected by using in this example, the final-condition values from the preceding example, thus: $\mathbf{T}_2 = P_2V_2\mathbf{T}_1/P_1V_1 = (3{,}718 \times 40 \times 120) \div (618.7 \times 20) = 17{,}846{,}300 \div 12{,}347 = 1{,}442°$ *F. abs.*

246. For Any Given Weight Of A Perfect Gas, The Quotient, Which Is Obtained By Dividing The Product Of Its Absolute Pressure And Volume By Its Absolute Temperature, Is A Constant; that is, the quotient has the same value for any condition of the gas. This is merely a statement, in words, of the fact which is expressed mathematically by For. (133). Or, the same fact stated in still another way is:

$$\frac{PV}{\mathbf{T}} = k \qquad \text{(constant)} \tag{144}$$

Wherein: P = the absolute pressure, which is exerted on or by any weight of the gas, in any pressure unit. V = the volume, of the same weight of gas when it is exerting the pressure P, in any volume unit. $\mathbf{T}$ = the absolute temperature, of the same weight of gas when it is exerting the pressure P, in any temperature unit. k = a constant value, for the given weight of gas, for any pressure-volume-temperature condition, the pressure, volume, and temperature respectively being always expressed in the same unit for each different condition. That is, this k represents a constant value in the same way that the value of k (Sec. 112) in the Boyle's-law formula remains constant for any given weight of a gas.

247. Values Of "k" For 1 Lb. Of Different Gases have been determined experimentally for practically all of the known gases. In this book such values are denoted by the symbol "k_G." They are, for some of the more common gases and for certain measurement units, given in Table 251. These Table 251 values hold only for 1 lb. of gas where: (1) *The volume is measured in cubic feet.* (2) *The absolute pressure is measured in pounds per square foot.* (3) *The temperature is measured in degrees Fahrenheit absolute.* If measurement units other than those just specified in (1), (2) and (3) are employed, then the k_G values will change accordingly.

Explanation.—In Determining Experimentally The Value Of k_G For A Given Gas, it is only necessary to measure simultaneously the: (1) *absolute pressure,* and the corresponding (2) *volume,* (3) *absolute*

temperature, and (4) *weight* of the quantity of gas under consideration. The quantity may be any that is convenient. Similarly, the pressure and the corresponding volume and temperature condition may be any that are convenient. Then, applying For. (144), multiply together the corresponding absolute pressure, P, and volume, V, and divide their product by the absolute temperature, **T**. The result will be k for the total quantity of gas under consideration. As stated in the preceding section, the value of k for any given weight of any certain gas will always be the same regardless of its pressure, volume and temperature condition. Then, by dividing the "k" value thus computed by the number of pounds in the total quantity of gas, the value of k for 1 lb., that is, the value of k_G is obtained. To explain the reason for this, suppose that 1 lb. of a gas, at a given temperature and pressure, occupies 1 cu. ft. It is obvious that, at the same pressure and temperature, 2 lb. of the gas must occupy 2 cu. ft., and **W** pounds must occupy **W** cu. ft. Now, since $k = PV/\mathbf{T}$ and since V varies directly as the weight of gas under consideration, it follows that k must also vary directly with the weight.

Note.—It Is Also True That, For Any Gas: k_G = [(*Its specific heat at constant pressure*) − (*Its specific heat at constant volume*)] × 778. This is here stated merely as an interesting fact; no endeavor will be made herein to explain the reason therefor.

Example.—It is found by experiment that 1 cu. ft. of air at atmospheric pressure and at a temperature of 32° F., weighs 0.080,71 lb. What is the gas constant, k_G, for air. Solution.—By definition, *atmospheric pressure* = 14.7 *lb. per sq. in. abs.* = 14.7 × 144 = 2116.8 *lb. per sq. ft. abs.* Also, taking the more accurate value of "459.6°," instead of the usual "460°" for the difference between the absolute zero and the Fahrenheit zero: 32° *F.* = 32 + 459.6 = 491.6° *F. abs.* Now substitute in For. (144) to obtain *the constant for this weight* (0.080,71 *lb.*) *of air* = $k = PV/\mathbf{T}$ = 2116.8 × 1 ÷ 491.6 = 4.306. The same constant "4.306" would be obtained, for this weight of air, for any other temperature—pressure—volume condition. Now divide by the weight of air to obtain *the gas constant for* 1 *lb. of air* = k_G = 4.306 ÷ 0.080,71 = 53.34, which is the same value as that given for air in Table 251.

248. The General Gas Law (The Perfect-gas Law) states the relation which exists between the pressure, volume, absolute temperature, and weight of a perfect gas. It is generally expressed as an equation as shown by For. (145). It is a very important law and one with which every engineer should be familiar because it recognizes in one equation every property of a given gas that may change, that is, which is variable. It is based on a combination of Boyle's, Charles' and Gay Lussac's laws, as is shown in the following derivation.

249. The General-gas-law Formulas are given below. Note that, in substituting in these formulas, *pounds-per-square-foot* absolute-pressure values and degrees Fahrenheit absolute-temperature values must be used. But these may readily be derived from gage-pressure and degree-Fahrenheit values, as explained in Secs. 17 and 62.

(145) $$PV = \mathbf{W}k_G\mathbf{T}$$ (pressure and volume)

hence, transposing:

(146) $$P = \frac{\mathbf{W}k_G\mathbf{T}}{V}$$ (lb. per sq. ft. abs.)

furthermore:

(147) $$V = \frac{\mathbf{W}k_G\mathbf{T}}{P}$$ (cu. ft.)

and:

(148) $$\mathbf{T} = \frac{PV}{\mathbf{W}k_G}$$ (deg. Fahr. abs.)

and:

(149) $$\mathbf{W} = \frac{PV}{k_G\mathbf{T}}$$ (lb.)

and:

(150) $$k_G = \frac{PV}{\mathbf{W}\mathbf{T}}$$ (gas constant)

and:

(151) $$D = \frac{\mathbf{W}}{V} = \frac{P}{k_G\mathbf{T}}$$ (lb. per cu. ft.)

Wherein: P = the absolute pressure of the gas, in pounds per square foot. V = the volume of the gas, in cubic feet. $\mathbf{W}$ = the weight of the gas, in pounds. k_G = a constant which varies with the kind of gas and with the units of measurement which are used; for the units here specified, values for different gases are given in Table 251. $\mathbf{T}$ = the absolute temperature of the gas in Fahrenheit degrees. D = the density of the gas, in pounds per cubic foot.

DERIVATION.—For. (144) is merely another way of expressing For. (133) which is derived, as there shown, by combining Boyle's, Charles' and Gay Lussac's laws. Now, For. (144) is for "any given weight of gas." That is, it assumes that the weight of gas under consideration is con-

stant. Thus, repeating For. (133) but using symbols which express: (1) *Pressure in pounds per square foot*, (2) *volume in cubic feet*, (3) *temperature in degrees Fahrenheit absolute*, there results:

(152) $$k = \frac{PV}{T}$$ (constant for any given weight of gas)

Now, by definition, k_G = *gas constant for* 1 *lb. of gas.* It was shown under Sec. 247 that if k_G, which is the gas constant for 1 lb. of the gas which is under consideration, be multiplied by **W**, which represents the total weight in pounds of the gas, the result will be k, the constant for the total amount of gas. That is:

(153) $$k = \mathbf{W}k_G$$ (constant for any given weight of gas)

Now, substituting the equivalent of k from For. (153) in For. (152) there results:

(154) $$\mathbf{W}k_G = \frac{PV}{T}$$

and then transposing:

(155) $$\mathbf{W}k_G\mathbf{T} = PV$$

which is the same as For. (145).

250. The General-gas-law Formulas Are The Engineer's Practical Working Formulas.—Any problem which can be solved by applying either Boyles', Charles', or Gay Lussac's laws can be solved with them. Furthermore, by their use many problems, to which none of these three laws apply, can be worked. Hence, they are the only formulas that need be memorized for any of these computations. The examples which are given below illustrate only a few of their many applications.

Note.—The General Gas Law Holds Only For Perfect Gases—as they are defined in Sec. 226 as do all of the other laws treated in this division. In fact, the following definition is sometimes given: *A gas which has properties such that it conforms exactly to the general gas law is a perfect gas.* But the performances of many ordinary gases conform sufficiently to the general gas law that, for the usual engineering computations, it provides results well within the limits of required accuracy.

251. Specific Heats, Values Of "k" And Values Of "k_G" For Some Of The More Common Gases.—Specific-heat values shown are average values over the temperature ranges (32°–400° F.) ordinarily encountered in practice. Values in line 9 are variable. All others are from Marks' "Mechanical Engineers' Handbook." See Sec. 247 for units which must be

employed when the k_G values are used. The substances of items 1, 2 and 10 are not to be treated as gases unless highly superheated; see Div. 11.

	Name of gas	Chemical symbol	Specific heat: At constant pressure, C_P	Specific heat: At constant volume, C_V	$k = C_P \div C_V$	k_G = Gas constant $= (C_P - C_V) \times 778$
1	Sulphur dioxide	SO_2	0.154	0.123	1.25	24.10
2	Carbon dioxide	CO_2	0.210	0.160	1.31	35.09
3	Oxygen	O_2	0.217	0.155	1.40	48.25
4	Air	.....	0.241	0.171	1.40	53.34
5	Nitrogen	N_2	0.247	0.176	1.40	54.99
6	Ethylene	C_2H_4	0.400	0.330	1.20	55.08
7	Carbon monoxide	CO	0.243	0.172	1.41	55.14
8	Acetylene	C_2H_2	0.350	0.270	1.28	59.34
9	Blast furnace	.....	0.245	0.174	1.40	55.05
10	Ammonia	NH_3	0.523	0.399	1.31	90.50
11	Methane	CH_4	0.593	0.450	1.32	96.31
12	Hydrogen	H_2	3.42	2.44	1.40	765.9

252. The Problems Which Can Be Solved With The General Gas Law, Fors. (145) to (151), are: (1) *Those in which values for four of the five properties—pressure, volume, temperature, weight, and kind of gas— of a quantity of gas are known for a certain condition and it is desired to determine the value of the fifth property for that condition.* (2) *Those in which values for four of the five properties of a quantity of gas are known for a first given condition and, for a second condition, two of the values change while the other three remain constant; then, knowing the final value of one of the changed properties, the value of the other changed property may be computed.*

EXAMPLE.—A vessel (Fig. 236) contains 5 lb. of air. The gage pressure is 20 lb. per sq. in. The temperature is 90° F. What is the cubical content of the vessel? SOLUTION.—The *absolute pressure* $= (20 + 14.7) \times 144 = 5{,}000$ *lb. per sq. ft.* The *absolute temperature* $= 460 + 90 = 550°$ *F. abs.* From Table 251, k_G *for air* $= 53.34$. Now substituting the known values in For. (147): $V = Wk_GT/P = (5 \times 53.34 \times 550) \div 5{,}000 = 29.3$ *cu. ft.*

Example.—A receiver (Fig. 237) contains 800 cu. ft. of compressed air at a gage pressure of 120 lb. per sq. in. Its temperature is 80° F. What is the weight of the air. Solution.—The *absolute pressure* = (120 + 14.7) × 144 = 19,400 *lb. per sq. ft.* The *absolute temperature* = 460 + 80 = 540° *F. abs.* From Table 251, k_G *for air* = 53.34. Now substitute in For. (149): $W = PV/k_GT$ = (19,400 × 800) ÷ (53.34 × 540) = 539 *lb.*

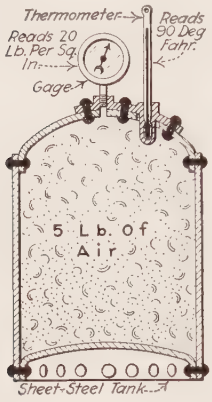


Fig. 236.—What is the volume of the vessel?

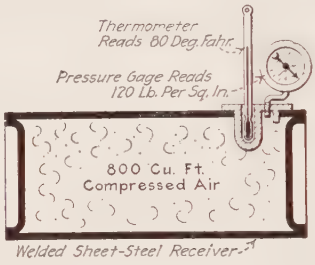


Fig. 237.—What is the weight of the air?

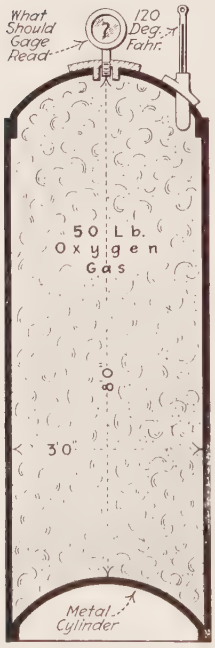


Fig. 238.—What is the gage pressure?

Example.—It is desired to store 50 lb. of oxygen gas in a metal cylinder (Fig. 238) which is 3 ft. in diameter and 8 ft. long. What must be the pressure shown by the gage on the tank when it contains 50 lb. of oxygen, if the oxygen is pumped in at a temperature of 120° F.? Solution.—The *volume of the* tank = 0.785 × 3 × 3 × 8 = 56.5 *cu. ft.* From Table 251, for oxygen, k_G = 48.25. The *absolute temperature* = 120 + 460 = 580° *F. abs.* Now substitute in For. (146): $P = Wk_GT/V$ = (50 × 48.25 × 580) ÷ 56.5 = 24,765 *lb. per sq. ft. abs. Pounds per square inch absolute* = 24,765 ÷ 144 = 171.9 *lb. per sq. in. abs. Gage pressure = absolute pressure* − 14.7 = 171.9 − 14.7 = 157.2 *lb. per sq. in. = pressure which should be shown by gage on cylinder.*

Example.—An air compressor pumps 120 cu. ft. per min. of free air (atmospheric pressure), which is at an average temperature of 70° F. Disregarding the effect of moisture in the air, what is the weight of the air which is pumped each minute? Solution.—From Table 251, for air, k_G = 53.34. Now, substitute in For. (149): $W = PV/k_GT$ = [(14.7 × 144) × 120] ÷ [53.34 × (70 + 460)] = [2,116.8 × 120] ÷ [53.34 × 530] = 254,016 ÷ 28,276 = 9.0 *lb.*

Example In Which The Values For Four Properties Are Known For A First Given Condition And, For A Second Condition, Two Of The Values Change While The Other Three Remain Constant, it being necessary to determine the final value of one of the changed properties: A steel container holds 800 cu. ft. of air which is at a pressure of 19,400 lb. per sq. ft. abs. and a temperature of 540° F. abs. What will be the pressure exerted by the air if its temperature is increased to 600° F. abs.? Solution.—From Table 251, for air, k_G = 53.34. Hence, by For. (149), $\mathbf{W} = PV/k_G\mathbf{T}$ = 19,400 × 800 ÷ (53.34 × 540) = 538.7 *lb.* Now substitute in For. (146): $P = \mathbf{W}k_G\mathbf{T}/V$ = 538.7 × 53.34 × 600 ÷ 800 = 21,567 *lb. per sq. ft. abs.*

253. The "Density" Of Any Substance is its mass per unit of volume. In engineering, density is usually considered as the weight of a unit volume of a substance—that is, if a body's weight be divided by its volume, the result is called its density. The weight and volume may be measured in any convenient units. If the weight be measured in pounds and the volume in cubic feet, the resultant density is expressed in *pounds per cubic foot.* This unit (lb. per cu. ft.) is very widely used in engineering work. The formula for density, expressed in this unit, is:

$$D = \frac{\mathbf{W}}{V} \qquad \text{(lb. per cu. ft.)} \tag{156}$$

which, by transposition, gives:

$$V = \frac{\mathbf{W}}{D} \qquad \text{(cu. ft.)} \tag{157}$$

and

$$\mathbf{W} = VD \qquad \text{(pounds)} \tag{158}$$

Wherein: D = the density of a substance, in pounds per cubic foot. $\mathbf{W}$ = its weight, in pounds. V = its volume, in cubic feet.

Example.—If 6 cu. ft. of water weigh 375 lb., what is the density of the water? Solution.—By For. (156), $D = \mathbf{W}/V$ = 375 ÷ 6 = 62.5 *lb. per cu. ft.*

Example.—If the density of air (under certain conditions) is 0.1 lb. per cu. ft., what volume will 8 lb. of air occupy? Solution.—By For. (157), $V = \mathbf{W}/D$ = 8 ÷ 0.1 = 80 *cu. ft.*

Example.—What weight of hydrogen will be contained in a 5-cu. ft. container if the density of the hydrogen is 0.03 lb. per cu. ft.? Solution.—By For. (158), $\mathbf{W} = VD$ = 5 × 0.03 = 0.15 *lb.*

254. The Density Of Any Substance Will Vary with its temperature or with any other property which affects its volume. Thus, since heating a solid expands it but does not (ordinarily) change its weight, it is obvious that heating will decrease the density of a solid. With gases, the density depends on the pressure, temperature, and kind of gas. With a given weight of a certain gas, the density varies with the pressure and temperature. Formulas for the density of a gas and for its variations with pressure and temperature are derived by substituting from For. (156) into the gas-law formulas which have already been developed. Thus, for a given weight of any gas at constant temperature (Boyle's law):

$$\frac{P_1}{P_2} = \frac{D_1}{D_2} \qquad \text{(ratio)} \tag{159}$$

or

$$D_2 = \frac{D_1 P_2}{P_1} \qquad \text{(final density)} \tag{159A}$$

at constant volume, (Charles' law):

$$D_1 = D_2 \qquad \text{(density)} \tag{160}$$

at constant pressure (Gay-Lussac's law):

$$\frac{\mathbf{T}_1}{\mathbf{T}_2} = \frac{D_2}{D_1} \qquad \text{(ratio)} \tag{161}$$

or

$$D_2 = \frac{D_1 \mathbf{T}_1}{\mathbf{T}_2} \qquad \text{(final density)} \tag{162}$$

For a given weight of any gas (combined law):

$$\frac{P_1}{D_1 \mathbf{T}_1} = \frac{P_2}{D_2 \mathbf{T}_2} \qquad \text{(ratio)} \tag{163}$$

or

$$D_2 = \frac{D_1 \mathbf{T}_1 P_2}{\mathbf{T}_2 P_1} \qquad \text{(final density)} \tag{164}$$

Now from For. (156) $D_F = \mathbf{W}/V$. Then, substituting this D_F for its equivalent in For. (151) for the general gas law, it follows that for any gas.

$$D_F = \frac{P_F}{k_G \mathbf{T}_F} \qquad \text{(lb. per cu. ft.)} \tag{165}$$

Wherein: D = density. P = absolute pressure. $\mathbf{T}$ = absolute temperature. The units may be any convenient ones; the subscripts $_1$ and $_2$ referring respectively to the initial and final conditions of a gas which undergoes a change of condition. D_F = density, in pounds per cubic foot. P_F = absolute pressure, in pounds per square foot. $\mathbf{T}_F$ = absolute temperature, in degrees Fahrenheit. k_G = gas constant, as given in Table 251.

EXAMPLE.—The density of a certain gas is 0.2 lb. per cu. ft. when under 200 lb. per sq. in. abs. pressure. What will be the density of the same gas under 30 lb. per sq. in. abs. and at the same temperature? SOLUTION.—By For. (159*A*), $D_2 = D_1P_2/P_1 = 0.2 \times 30 \div 200 = 0.03$ *lb. per cu. ft.*

EXAMPLE.—If the density of air is 0.15 lb. per cu. ft. when under a certain pressure and at 40° F., what will be its density when under the same pressure but at 1,140° F.? SOLUTION.—By For. (162), $D_2 = D_1\mathbf{T}_1/\mathbf{T}_2 = 0.15 \times (40 + 460) \div (1{,}140 + 460) = 0.15 \times 500 \div 1{,}600 = 0.047$ *lb. per cu. ft.*

EXAMPLE.—A given weight of gas, when under 30-in. mercury column and at 60° F. has a density of 0.06 lb. per cu. ft. What will be its density when under 10 in. mercury column and at 20° F.? SOLUTION.—By For. (164), $D_2 = D_1\mathbf{T}_1P_2/\mathbf{T}_2P_1 = 0.06 \times (60 + 460) \times 10 \div [(20 + 460) \times 30] = 0.06 \times 520 \times 10 \div (480 \times 30) = 0.021{,}7$ *lb. per cu. ft.*

EXAMPLE.—What is the density of oxygen at atmospheric pressure and 32° F.? SOLUTION.—From Table 251, k_G (for oxygen) = 48.25. Hence by For. (165): $D_F = P_F/k_G\mathbf{T}_F = (14.7 \times 144) \div (48.25 \times 492) = 0.089{,}2$ *lb. per cu. ft.*

255. Table Of Absolute And Relative Densities Of Various Gases. (Based on values in Marks' "Mechanical Engineers' Handbook," p. 316). Carbon dioxide and ammonia, at the pressure and temperature given, are sufficiently superheated that they may reasonably be considered as gases.

Kind of gas	Absolute density in lb. per cu. ft., at atmospheric pressure, or 14.7 lb. per sq. in. absolute		Relative density as compared to air
	64° F.	32° F.	
Air	0.0761	0.0807	1.000
Oxygen	0.0840	0.0892	1.105
Nitrogen	0.0737	0.0783	0.970
Hydrogen	0.00529	0.00562	0.0696
Carbon monoxide	0.0734	0.078	0.968
Carbon dioxide	0.1156	0.1227	1.520
Ammonia	0.04483	0.0476	0.590
Acetylene	0.0684	0.0725	0.899
Methane	0.0421	0.0447	0.554
Ethylene	0.0738	0.0780	0.969

256. Air Drafts Are Caused By Differences In The Density Of The Air.—When a body of air is heated it expands; its density decreases. It thus becomes lighter per unit of volume. Therefore, it tends to ascend, due to its displacement by the cooler and heavier air from above. Thus the less dense air is forced upward by the denser air above it just as a cork is forced upward in water by the denser water above it. Toy balloons (Fig. 239), also many balloons which are built for actual service, derive their buoyancy from the low-density hot air and combustion gases

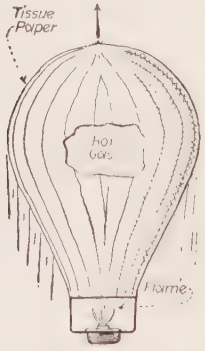


Fig. 239.—Hot gas lifts the toy balloon.

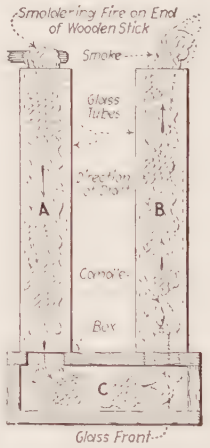


Fig. 240.—Air-draft produced by heat.

with which they are inflated. The draft (see the author's Steam Boilers) which is produced by all chimneys, power-plant and others, likewise depends upon this principle.

Example.—Two glass chimney-tubes, *A* and *B* (Fig. 240) are placed over apertures in a box, *C*, which has a glass side. A lighted candle is placed in the tube *B*. Thereby the air in tube *B* becomes heated and

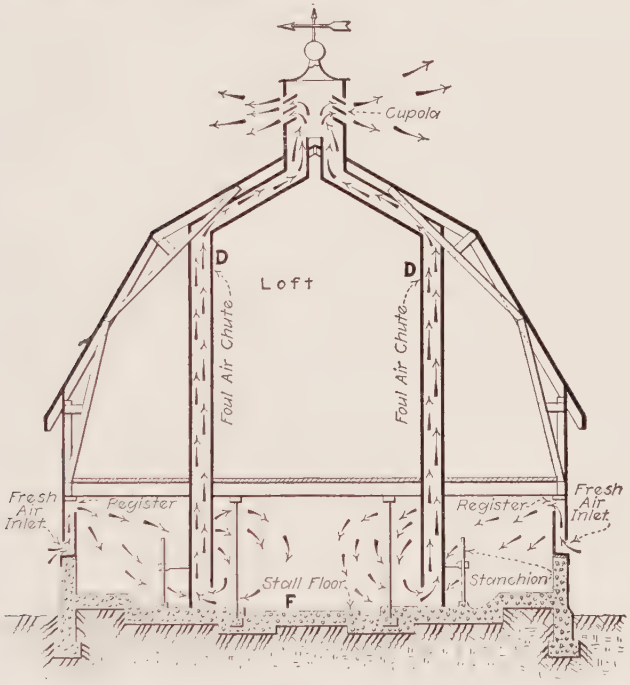


Fig. 241.—Barn ventilated by rising warm-air currents. (The air in the stall floor, *F*, becomes warmer than the outside air due to the heat given off by the animals. It is then displaced by colder outside air and forced up through ducts, *D*.)

its density decreases. Therefore it rises, due to its displacement by the cooler denser air which decends through tube *A*. A draft is thus produced which forces the smoke downward from the smoldering fire at the top of *A*. The smoke can then be seen flowing down through chimney *A* into the box, *C*, and thence upward through chimney *B*. See also Fig. 241.

Example.—Each of the chimney-tubes, *A* and *B* (Fig. 240) is assumed to be 100 ft. high and of 1 sq. ft. cross-section. The temperature in tube *A* is 64° F., and in tube *B* 464° F. What pressure, in inches water column, tends to force the smoke up through tube *B*? Solution.—By

Table 255 the *density of the air in tube A under atmospheric pressure at* 64° *F.* = 0.076,1 *lb. per cu. ft.*, the *absolute temperature in tube A* = 460 + 64 = 524° *F. abs.*, and in tube *B* = 460 + 464 = 924° F. abs. By For. (162) the *density of the air in tube B* = $D_2 = D_1\mathbf{T}_1/\mathbf{T}_2$ = (0.076,1 × 524) ÷ 924 = 0.043,2 *lb. per cu. ft.* The *volume of air in each tube* = 100 × 1 = 100 *cu. ft.* Hence, the *weight of the air in tube A* = 100 × 0.076,1 = 7.61 lb., while the *weight of the air in tube B* = 100 × 0.043,2 = 4.32 *lb.* Therefore, the *boosting pressure in tube B* = 7.61 − 4.32 = 3.29 *lb. per*

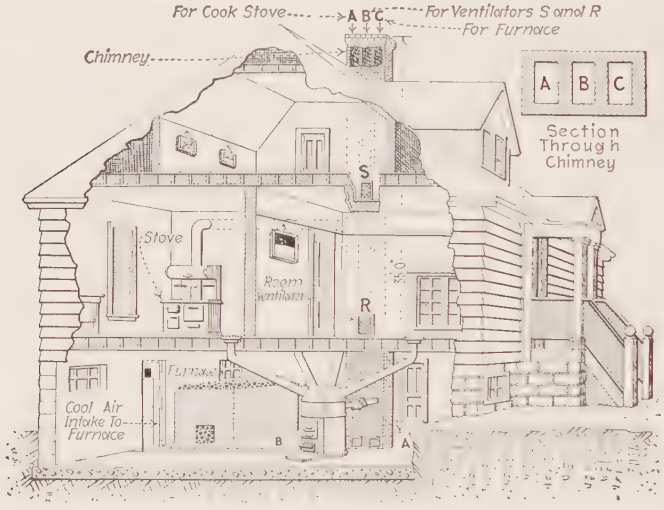


Fig. 242.—Illustrating chimney draft (the three-flue chimney provides draft for the furnace and cook-stove and also, by means of ventilators, *S* and *R*, ventilates the rooms).

sq. ft. = 3.29 ÷ 144 = 0.022,8 *lb. per sq. in.* By For. (9) the *equivalent height of water column* = P_I = 27.684*P* = 27.684 × 0.022,8 = 0.634 *in. water column.*

Example.—The chimney of a dwelling (Fig. 242) extends 35 ft. above the furnace in the basement. The temperature of the outside air is 32° F. The average temperature of the gases inside the chimney is 450° F. What is the draft pressure produced thereby, in inches of water-column? Solution.—By Table 255 *the density of air at* 32° = 0.080,7 *lb. per cu. ft.* By For. (162), the approximate *density of the combustion gases in the chimney* = $D_2 = D_1\mathbf{T}_1/\mathbf{T}_2$ = 0.0807 × (460 + 32) ÷ (460 + 450) = 0.043,6 *lb. per cu. ft.* The *pressure of the column of chimney gases* (on line *AB*, coinciding with furnace grate) = 35 × 0.043,6 = 1.53 *lb. per sq. ft.* The *pressure, of an equivalent column of the external air* = 35 × 0.080,7 = 2.87 *lb. per sq. ft. of base area.* Hence, the *draft-pressure* = 2.82 − 1.53 = 1.29 *lb. per sq. ft.* = 1.29 ÷ 144 = 0.008,96 *lb. per sq. in.* By For. (9), the *equivalent height of water column* = P_I = 27.684*P* = 27.684 × 0.008,96 = 0.248 *in. water column.*

257. The Heat Effects In Gases Are Different From Those In Solids And Liquids.—As explained in Secs. 96 and 102, (Div. 4), the addition of heat to a *solid* body always produces an increase in its temperature (the heat does vibration work, Sec. 97, and does only an inappreciable amount of external work (Sec. 99). If the solid is at its melting temperature, then the addition of heat does disgregation work (Sec. 98) and an almost inappreciable amount of external work. Likewise, the addition of heat to a *liquid* always increases its temperature (does vibration work) and does only an inappreciable amount of external work; if the liquid is at its boiling temperature, then the addition of heat does disgregation work and an appreciable amount of external work. But, the addition of heat to *gas* at any temperature may or may not increase its temperature, may or may not do external work, and, as will be shown, never does any disgregation work. Whether or not vibration or external work is done, depends on the rates at which the gas is heated and at which it is permitted to do external work. The gas temperature may even increase without the addition of any heat from without. These phenomena will be explained in following sections.

258. No Disgregation Work Is Done When A Perfect Gas Is Heated Or Cooled.—The truth of this statement was first shown by Joule with the apparatus shown in Fig. 243. Later experiments by Lord Kelvin (Sir William Thompson) revealed that Joule's results were slightly in error. The experiment is now frequently referred to as the "Joule-Thompson effect."

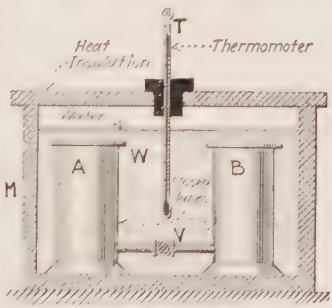


FIG. 243.—The apparatus which was used by Joule to prove that no disgregation work is done when a gas expands.

EXPLANATION.—Joule placed two equal-sized containers (*A* and *B*, Fig. 243) in a tank of water, *W*, and provided a very sensitive thermometer, *T*, for measuring the temperature of the water. The tank, *W*, was well insulated to prevent heat flow into or out of *W*. He compressed air into *A* until the pressure was 22 atmospheres and exhausted all of the air from *B*. After the whole apparatus had reached the temperatures

of the room, he opened the valve, V, in the pipe which connected A and B and watched T to observe how the temperature would vary. He could observe no variation.

Now, as explained in Sec. 96, the three ways in which heat may be expended are as vibration work, disgregation work, and external work. This thought is expressed by For. (50) which is repeated here:

$$Q = Q_V + Q_D + Q_E \quad \text{(B.t.u.)} \tag{166}$$

Wherein: Q = heat added to the substance. Q_V = heat expended in doing vibration work. Q_D = heat expended in doing disgregation work. Q_E = heat expended in doing external work. All quantities being expressed in British thermal units.

Now, in Joule's experiment: (1) No heat was added to or abstracted from the air because the whole apparatus was insulated and was at room temperature. Hence $Q = 0$. (2) No change in temperature was noted. Hence, no vibration work was done, and $Q_V = 0$. (3) No external work was done by the air because there was no means of conveying it to or from the apparatus. Hence, $Q_E = 0$. Therefore, by substituting the values obtained in Joule's experiment into For. (166), after transposing there results: $Q_D = Q - Q_V - Q_E = 0 - 0 - 0 = 0$. Hence, it was concluded that for air $Q_D = 0$.

The later experiments by Lord Kelvin showed that, although the temperature remains *nearly constant* in the above-described experiment, there is a slight variation. The variation is very slight for the "permanent" gases (Sec. 348) at ordinary temperatures and it is assumed that for a perfect gas (Sec. 226) there would be no variation. The variation for actual gases grows larger, the lower the temperature at which the experiment is performed. The reason for this is that the gases become more and more like vapors, Div. 11, as their liquefaction temperatures are approached.

259. Heat Transferred To (Or From) A Perfect Gas May Produce (Is Produced By) Either Or Both Of Two Effects—Vibration Work And External Work.—Since it is possible to increase the temperature of a gas by heating it, it is obvious that heat energy, when added to a gas, can do vibration work. Furthermore, since heating a gas often causes it to expand or increase in volume, it is also obvious that the added heat energy can cause the gas to move substances (moving M and W in Fig. 233 for example) which restrict its volume. That is, the added heat energy can cause the gas to do external work. In any case, the amounts of vibration work and external work that are produced depend on the rate at which expansion is permitted to proceed.

Example.—Suppose, Fig. 244, that a certain weight of gas is confined in a cylinder which is fitted with a handled piston, thermometer, and pressure gage. At 70° F., and 30 lb. per sq. in. abs. the gas is found to occupy 1 cu. ft. (condition *a*, Fig. 244). The piston is now held in the position shown while heat is applied to the cylinder until the thermometer reads 600° F. The gage will now show a pressure of 60 lb. per sq. in. abs. (by Charles' law, Sec. 237). But, since the gas did not force out the

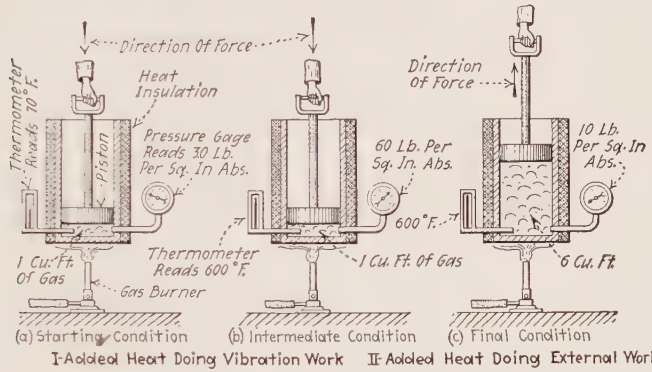


Fig. 244.—Illustrating how the heat energy which is added to a gas may do either vibration work or external work.

piston, it did no external work. Hence, the heat added in passing from condition *a* to condition *b* was all used in raising the temperature of the gas—in doing vibration work.

When condition *b* is reached, the heating is continued but, instead of holding the piston in one position, the operator now, partially restraining it, permits the piston to rise at such a rate that the thermometer continually shows 600° F. After an interval, the volume of the gas will have increased to 6 cu. ft. and the pressure will have decreased to 10 lb. per sq. in. abs. (condition *c*, Fig. 244). In passing from condition *b* to condition *c*, the gas has done external work in forcing out the piston against the resistance of the operator's hand but, since the temperature remained constant, no vibration work was done. Hence, in *II*, the heat energy was all used in doing external work.

260. A Gas Generally Does External Work When It Expands.—All gases exert pressure. If a gas is confined in a closed vessel, it exerts pressure on the walls of the vessel because the gas molecules, in their vibratory motion, strike the walls of the vessel (Sec. 50). Therefore, the walls of the vessel provide a resistance to the pressure of the gas. If the gas is permitted to expand, then the walls of the vessel or a part of them must have been moved. This motion of the walls

of the vessel constitutes an instance of motion against resistance (which is work, Sec. 20). But the pressure of the gas has aided in (or been the entire cause of) the motion of the walls of the vessel. Hence, the gas has, by reason of its pressure, done external work.

Explanation.—Assume that a certain weight of gas is confined between the end of a cylinder A, Fig. 245, and a piston, M, which has been inserted through the open end of the cylinder. The gas exerts a certain pressure against the face of the piston. This pressure tends to force the piston out of the cylinder (in the direction of the arrow). If the piston is permitted to move to the position N, the gas must have aided in the piston's motion. Therefore, the gas has done external work.

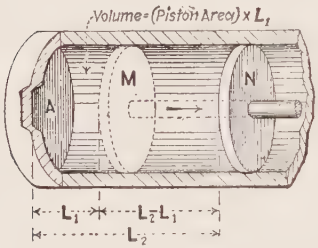


Fig. 245.—Showing that an expanding gas does external work.

Note.—A Throttling Or Frictional Expansion is one during which no external work is done by the expanding fluid. This occurs when a gaseous substance flows through a small opening from a region of high pressure to one of lower pressure, gaining velocity as it flows, which velocity is then destroyed. The substance is said to do work on itself as it increases its velocity—the work being stored in the substance in the form of kinetic energy. But, when the kinetic energy disappears as the velocity again decreases, the kinetic energy is reconverted into heat energy. Instances of throttling expansion are: (1) Joule's experiment, Sec. 258. (2) The pressure drop which accompanies the flow of a gaseous fluid through a pipe or restricted opening. Throttling expansions will not be further discussed in this division. See Sec. 387 for the throttling expansion of vapors.

261. Work May Be Represented Graphically By An Area.—As defined in Sec. 21, *work* is the product of *force* times *distance*. Since the area of any figure or diagram is the product of a length times a height, it is possible to so draw a figure that its length shall represent a distance (or force) and that its height shall represent a force (or distance). Then, its area must represent work (see explanation below). It will also be shown that work may be represented by a figure whose height represents pressure and whose length represents volume.

Explanation.—Assume that a constant force of 12 lb. is required (Fig. 246) to move an object in a given direction and that the object is

moved 8 ft. from a starting point by this force. A rectangle *OBCD*, Fig. 247, is drawn, 12 units in height and 8 units in length. Its area ($12 \times 8 = 96$ *squares*) then represents 96 units of work. Since each

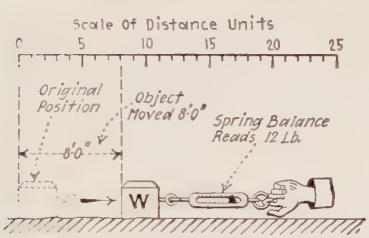


FIG. 246.—Object *W* moved 8 ft. by a constant force of 12 lb.

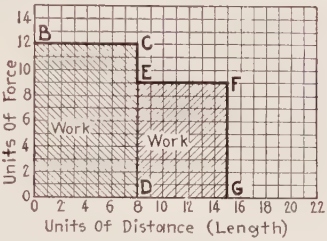


FIG. 247.—A force-distance work diagram. The shaded areas represent work.

unit of height represents 1 lb. and each unit of length represents 1 ft., each unit of area represents 1 lb. × 1 ft. or 1 ft.-lb. Hence, the area *OBCD* represents 96 ft.-lb. of work. If, now, a constant force of 9 lb. is required (Fig. 248) to move the object from the 8-ft. mark to a 15-ft. mark (measured from the same starting point as above), the force of 9 lb. will act through a distance of (15 − 8) or 7 ft. Hence, for this second movement the *work done* $= 9 \times 7 = 63$ *ft.-lb.* as represented by the area *DEFG*, Fig. 247.

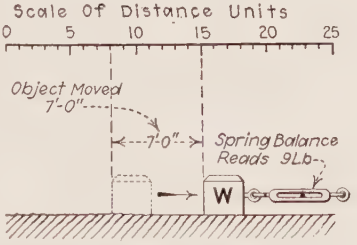


FIG. 248.—Object *W* moved 7 ft. by a constant force of 9 lb.

Assume, in a second case (Fig. 249), that a constant force of 48 lb. acts through a distance of 40 ft. A unit of height may be taken to represent a force of 4 lb. Then the 48-lb. force will be represented by 12 units (*OB*, Fig. 247). A unit of length on the diagram may be taken to represent 5 ft. Then, the 40-ft. distance will be represented, by 8 units

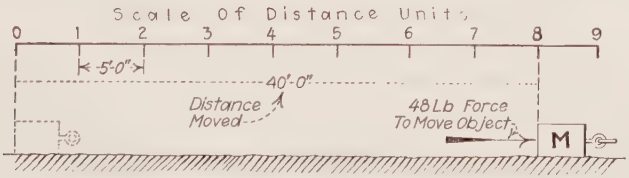


FIG. 249.—Object *M* is moved 40 ft. by a 48-lb. force.

(*OD*, Fig. 247). The work done by the force will then be represented, as in the first case by the area *OBCD* or 96 area work units. But now each area unit represents 4 *lb.* × 5 *ft.* = 20 *ft.-lb.* Hence, in this case, the area

OBCD represents $96 \times 20 = 1{,}920$ *ft.-lb.* which is the work done by the 48-lb. force acting through a distance of 40 ft.

Note.—The Area Under A Force-distance Graph Also Represents The Work Done When The Force Is Not Constant.—If, Fig. 250, in acting through the first 4 ft., a force increases uniformly from 4 to 6 lb., then *the work done* = (*average force*) $\times$ (*distance*) = $[(4 + 6)/2] \times 4 = 5 \times 4 = 20$ *ft.-lb.* which is the area of the figure *ABCD*. Then, if in acting through the next 4 ft. the force increases to 7 lb., the average force will be 6.5 lb. and the *work done* $= 6.5 \times 4$ or 26 *ft.-lb.*, as represented by the area *DCEF*. If then the force in acting through the next 6 ft. decreases uniformly to 5 lb., the average force will be 6 lb. and the *work done* $= 6 \times 6$ *or* 36 *ft.-lb.*, as represented by the area *FEGH*. Thus the area *ABCEGHA* represents the total work done by the varying force in acting through the total distance of 14 ft. That is, *total work done* $= 20 + 26 + 36 = 82$ *ft.-lb.*

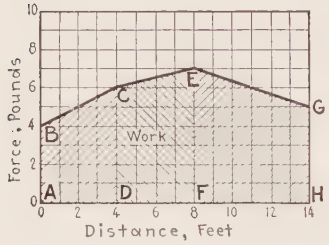


Fig. 250.—Force-distance "work" diagram for a varying force.

262. The Area Under A Pressure-volume Graph Also Represents Work, as is explained below. The pressure-volume graph can readily be drawn for an expanding (or compressed) gas. Hence, the finding of the area under such a graph affords a convenient means for finding the work done by the gas during its expansion or on the gas during its compression.

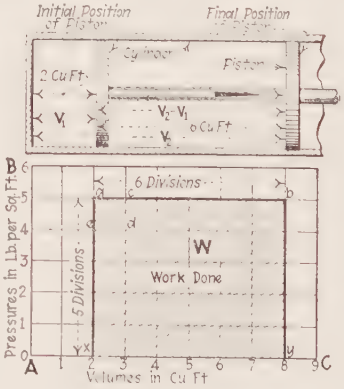


Fig. 251.—Pressure-volume work diagram showing work done by expansion. (Absolute pressure in cylinder is assumed to remain constant.) *Work done* = *Volume* $\times$ *Pressure* $= (8 - 2) \times 5 = 6 \times 5 = 30$ *ft.-lb.*

Explanation.—Assume that (Fig. 251) a cylinder is fitted with a tight-fitting piston between which and the end of the cylinder there is a volume, V_1, of 2 cu. ft. of a gas at a pressure of 5 lb. per sq. ft. abs. Assume that, by heating, the gas is caused to expand at constant pressure to a volume, V_2, of 8 cu. ft. Plot, as shown by the lower diagram in Fig. 251, pressures along the vertical scale *AB* and volumes along the horizontal scale *AC*. The line *ab* will represent the

expansion of the gas. Since each unit of volume represents 1 cu. ft., each division such as *ac* which represents 1 cu. ft., must also represent a certain distance through which the piston was moved. If the area of the piston in square feet is denoted by the symbol A_P, then *ac* will denote a distance of: 1 *cu. ft.* $\div$ A_P *sq. ft.* $= 1/A_P$ *ft.* Also, since a pressure of 1 lb. per sq. ft. is represented by each vertical division on the graph, each division such as *ea* must also represent a certain force on the piston. This force is *pressure* $\times$ *area* $= 1 \times A_P$ *lb.* Hence, each square of the area, W, such as *acde*, must (see explanation under Sec. 261) represent $(1/A_P) \times (1 \times A_P) = 1$ *ft. lb.* Therefore, the work done by the expanding gas is represented by the area *xaby* or $5 \times 6 = 30$ *ft.-lb.*

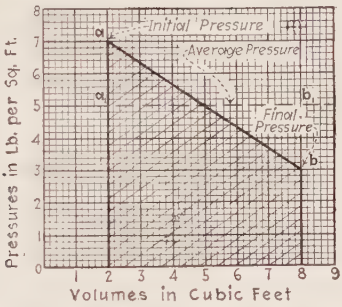


Fig. 252.—Pressure-volume work diagram with falling pressure. (*Work Done* = *Volume* $\times$ *Pressure* $= (8 - 2) \times 5 = 6 \times 5 = 30$ *ft.-lb.*

Note.—The Area Under A Pressure-volume Graph Also Represents Work When The Pressure Is Not Constant.—Thus, if the pressure behind the piston of Fig. 251 had varied as shown by the line

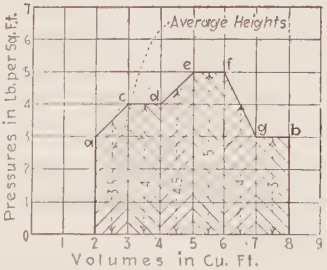


Fig. 253.—Work diagram with rising and falling pressures. Since the areas under each of the lines *ac*, *cd*, *de*, etc. are each 1 unit wide, the work done along *each* line (*ac*, *cd*, etc.) in foot-pounds is numerically equal to the average height shown. (The total work done may be computed thus: The average *height of strip ac*32 $= (3 + 4) \div 2 =$ 3.5; of *cd*43 $= 4$; of *de*54 $= (4 + 5) \div 2 =$ 4.5; of *ef*65 $= 5$; of *fg*76 $= (5 + 3) \div 2 =$ 4; and of *gb*87 $= 3$. Hence, for this diagram, the *average pressure* $= (3.5 + 4 + 4.5 + 5 + 4 + 3) \div 6 = 4$ *lb. per sq. ft.* The horizontal length of the diagram indicates: *displacement volume* $= 8 - 2 = 6$ *cu. ft.* Hence, as indicated by the hatched area of the diagram, *work done* = *pressure* $\times$ *volume* $= 4 \times 6 = 24$ *ft.-lb.*)

ab in Fig. 252, then the average pressure would have been 5 lb. per sq. ft. as indicated by the dashed line a_1b_1 and the work done would be represented by the shaded area of 30 ft.-lb. The finding of the work done for different variations of the pressure is shown in Figs. 253 and 254. Where

greater accuracy is required than can be obtained by using vertical strips 1 cu. t. wide, the diagram may be divided into strips each having a width of only a fraction of 1 cu. ft. as in Fig. 255. For the greatest accuracy, a planimeter or area-measuring instrument is employed (see the author's "Steam Engine Principles and Practice" and also Sec. 503).

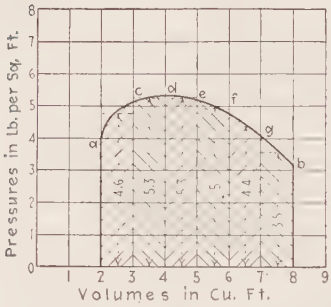
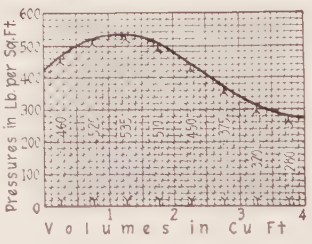


FIG. 254.—Work diagram with continuously varying pressure. The number of foot-pounds represented by each vertical strip is found exactly as in Fig. 253. As represented by the hatched area: *Total work done* = *Pressure* × *Volume* = [(4.6 + 5.3 + 5.3 + 5 + 4.4 + 3.5) ÷ 6] × (8 − 2) = 4.68 × 6 = 28.1 *ft.-lb.*

NOTE.—IN THERMODYNAMIC COMPUTATIONS, VOLUMES ARE ALWAYS, UNLESS OTHERWISE SPECIFIED, TAKEN IN CUBIC FEET AND PRESSURES IN POUNDS PER SQUARE FOOT. This is to insure that the work values which result from the computations will be in foot-pounds. Why this is true may be understood from a consideration of the following derivation.

FIG. 255.—Another pressure-volume work diagram. The work diagram is divided into strips each ½ cu. ft. wide, the average height of each strip being indicated. The work represented by each strip is therefore equal to (½ the average height of the strip) ft.-lb. The total work done, which is represented by the hatchted area, may be computed thus: *Average pressure* = (460 + 520 + 535 + 510 + 450 + 375 + 320 + 280) ÷ 8 = 431.25 *lb. per sq. ft. Displacement volume* = 4 *cu. ft.* Hence, *total work done* = *Pressure* × *Volume* = 431.25 × 4 = 1,725 *ft.-lb.*



263. To Compute The Work Done By The Expansion, Or In The Compression, Of A Gas Or Vapor When The Average Pressure And The Initial And Final Volumes Are Known, use the following formulas:

By expansion:

(167) $$W = P(V_2 - V_1)$$ (foot-pounds)

By compression:

(168) $$W = P(V_1 - V_2)$$ (foot-pounds)

Wherein: W = work done by the gas or vapor in expanding or done on the gas or vapor in compressing it, in foot-pounds. P = average absolute pressure exerted by (or on) the gas

during its expansion (or contraction), in pounds per square foot; this is the average of *all* of the pressures—not merely the mean of the initial and the final pressures. V_2 = final volume of the gas, in cubic feet. V_1 = initial volume of the gas, in cubic feet.

Examples.—See Figs. 215, 252, 253, 254 and 255 for examples which illustrate the application of the above formula. Certain of these illustrations also show how the *average absolute pressure*, P, is computed.

Derivation.—When the piston (Fig. 215) stands at M, the volume of space between the piston and the cylinder head may be expressed by:—

$$V_1 = AL_1 \qquad \text{(cubic feet)} \tag{169}$$

Wherein: V_1 = the volume, due to position M, in cubic feet. A = the area of the piston, in square feet. L_1 = the distance, due to position M, between the piston and the cylinder head, in feet. When the piston is moved to N, then the volume of space between the piston and the cylinder-head may, similarly, be expressed by:

$$V_2 = AL_2 \qquad \text{(cubic feet)} \tag{170}$$

Wherein: V_2 = the volume, due to position N, in cubic feet. L_2 = the distance due to position N, between the piston and the cylinder head, in feet. Now, the average force exerted in moving the piston from M to N may be expressed by:—

$$F = AP \qquad \text{(pounds)} \tag{171}$$

Wherein: F = the average force, in pounds, exerted against the piston. P = the average pressure against the piston, in pounds per square foot. A = piston area, in square feet, as before. Now, the work which is done, due to the movement of the piston against an external force, may be expressed by:

$$W = F(L_2 - L_1) \qquad \text{(foot-pounds)} \tag{172}$$

Wherein: W = the work done, in foot-pounds. $(L_2 - L_1)$ = the distance through which the piston moves, in feet. F = the average pushing force, in pounds, as above. Now substituting for F in For. (172), its equivalent AP from For. (171) there results:

$$W = AP(L_2 - L_1) = P(AL_2 - AL_1) \qquad \text{(foot-pounds)} \tag{173}$$

Now substituting in For. 173 for AL_2 and AL_1, their equivalents V_2 and V_1 from Fors. (170) and (169), there results:

$$W = P(V_2 - V_1) \qquad \text{(foot-pounds)} \tag{174}$$

which is For. (167). By a similar process of reasoning For. (168) for compression may be derived.

Note.—The Imaginary Graph Of Fig. 252 and certain others which immediately precede and follow, are included only to illustrate the general principle under discussion. The values obtained by the actual

expansion of gases and in heat engine practice are always, as will be shown, such that that they will not plot into simple straight-line graphs.

264. The "Effective Work" Done By An Expanding Gas is equal to the *total* work minus the *back-pressure* work. The discussion of the preceding sections concerned only the total work as do most of the following sections. However, as is explained below, when a gas expands behind a piston the other side of which is subject to atmospheric or other pressure, then only a portion of the work done by the gas on the piston, is effective in doing useful work

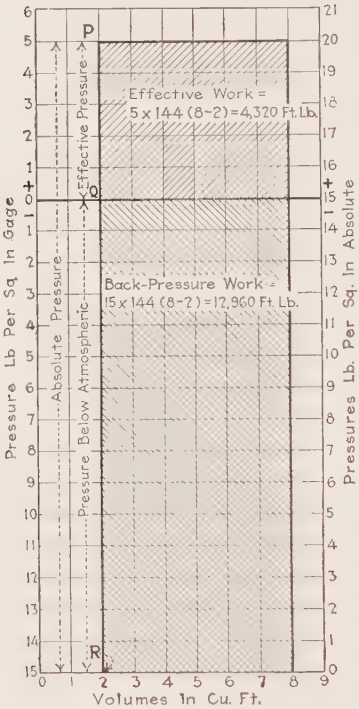


FIG. 256.—Pressure-volume diagram for gas expanding in atmosphere at 5 lb. per sq. in. gage constant pressure.

EXPLANATION.—Suppose that the piston of Fig. 251 is subjected at its right or open end to atmospheric pressure and that the pressure of the expanding gas within the cylinder remains 5 lb. per sq. in. *gage* during the expansion. Then the work diagram for the expansion will be as represented in Fig. 256. A total pressure *RP* due to the expanding gas is tending to force the piston to the right, but a pressure *RQ* is tending to force the piston to the left. The total shaded area (17,280 ft. lb.) then represents the total work done by the expanding gas but the lower portion of the area represents work done (12,960 ft.-lb.) in overcoming the resistance of the atmosphere and only the upper portion of the area (4,320 ft.-lb.) represents the work available or "effective" for overcoming additional resistances. Hence, the lower area is called the *back-pressure work*, whereas the upper area is called the *effective work*. Their sum is called the *total* work.

Note that, when the pressure is plotted in pounds per square inch, the work is found by multiplying the product of the pressure and the volume change by "144" which is the number of square inches in 1 sq. ft. Each unit of height on the graph represents a pressure of 1 lb. per sq. in. or 144 lb. per sq. ft.

265. The Specific Heat Of A Gas May Have Any Value whatsoever depending on how much work the gas is permitted to do as it is heated. See Sec. 88 for the definition of "specific heat." As was explained in Sec. 259, the heat which is added to a gas can be expended in either or both of two ways—in raising its temperature and in doing external work. Hence, the quantity of heat that must be added to each 1 lb. of a gas as its temperature is increased 1° F. (its specific heat) consists of two parts—(1) *The vibration heat.* (2) *The external-work heat.* The vibration heat is always the same for 1 lb. of a given gas heated through 1° F. but, as will be shown, the external-work heat will depend on the quantity of work that the gas is permitted to do while its temperature is being raised. Since the gas may expand in any number of ways or may be compressed while it is heated, it follows that, as above stated, the specific heat may have any value whatever. Certain principal values of the specific heats of gases will be discussed in following sections.

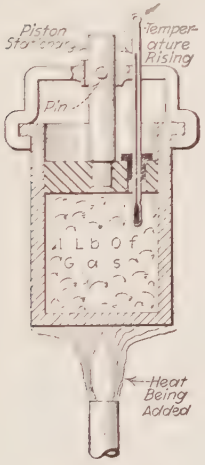


Fig. 257.—Heating a gas which cannot expand and hence can do no external work.

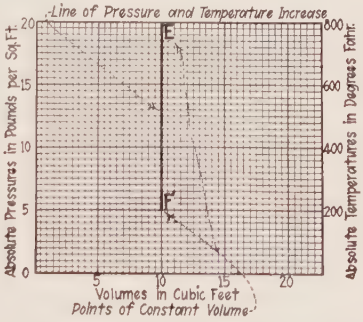


Fig. 258.—"Work diagram" for a constant-volume, pressure and temperature change—(10 cu. ft. of gas at 5 lb. per sq. ft absolute and 200° F. absolute = 10 cu. ft. of gas at 20 lb. per sq. ft. absolute and 800° F. absolute, but no external work is done).

266. The Specific Heat Of A Gas When Its Volume Is Maintained Constant, Fig. 257, is a very useful value. It will be represented by C_v and referred to as *specific heat at constant volume.* By Charles' law (Sec. 237) the pressure of a given

weight of gas, when heated in a constant volume, varies directly as its absolute temperature. Hence, the *pressure-volume graph for a constant-volume heating* is a vertical straight line *FE*, Fig. 258, under which there is no area. This is as may be expected for, when a gas does not expand its volume does not change and hence it does no work. Therefore all of the heat added to a gas at constant volume is vibration heat and is effective only in raising its temperature. The specific heats of various gases at constant volume are given in Table 251.

267. The Specific Heat Of A Gas When Its Pressure Is Maintained Constant, Fig. 259, is another very useful value.

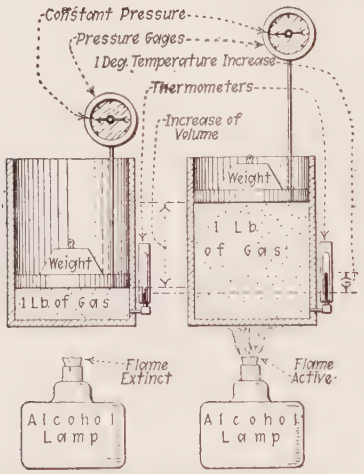


Fig. 259.—Heating a gas at constant pressure—gas expands as it is heated and does work in moving the piston upward.

It will be represented by C_P and will be referred to as *specific heat at constant pressure.* More heat is required to heat a gas through 1° F. at constant pressure than at constant volume because at constant pressure the gas expands, Fig. 259, and does external work. Enough heat must be added to increase the temperature and, besides this, the heat equivalent of the external work must also be added. It is interesting to note that for a given gas, C_P is independent of the pressure under which the gas is heated (see example below).

EXAMPLE.—If 1 lb. of air at 32° F. is confined in a volume of 1 cu. ft., it will, by For. (146), be under a pressure of 26,250 lb. per sq. ft. abs.

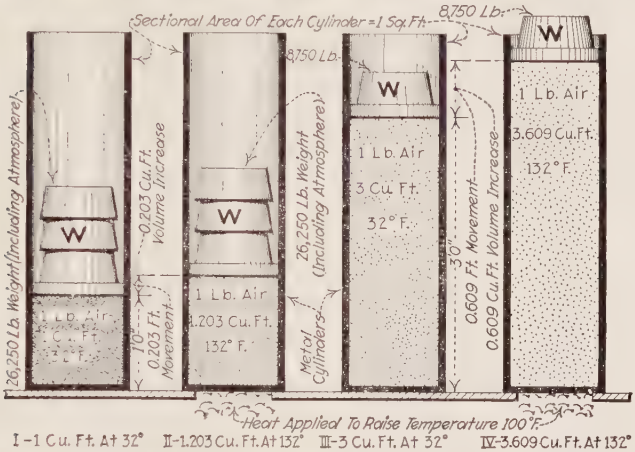


FIG. 260.—Showing how the specific heat of a gas at constant pressure is a constant for all pressures. (In each case the weight value indicated is the total weight on the gas including weight of piston and atmospheric pressure.)

(Fig. 260-*I*). As the air is heated at constant pressure to 132° F. its volume will increase to 1.203 cu. ft. (Fig. 260-*II*). Hence, the *external work done by the gas* = (*pressure*) × (*volume change*) = 26,250 × 0.203 = 532 *ft.-lb.* Therefore, the *heat added*

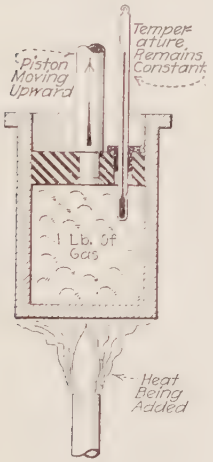


FIG. 261.—When a gas expands and is heated simultaneously at such rates that its temperature remains constant, its specific heat is infinite. See also Fig. 262.

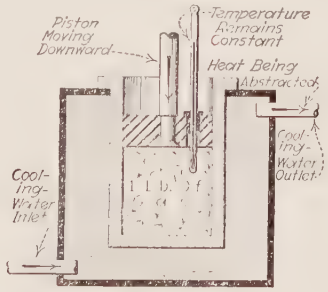


FIG. 262.—When a gas is simultaneously cooled and compressed at such rates that its temperature remains constant during the process, its specific heat is infinite.

$= C_V (T_2 - T_1) + (532/778) = 0.171 \times 100 + 0.684 = 17.784$ *B.t.u.* If, however, the 1 lb. of air at 32° F. occupied a volume of 3 cu. ft.,

its pressure would be 8,750 lb. per sq. ft. (Fig. 260-*III*). On being heated to 132° F. it would expand to 3.609 cu. ft. (Fig. 260-*IV*) and the *external work done* = 8,750 × 0.609 = 532 *ft.-lb.* as before. Hence 17.784 B.t.u. must have again been added in passing from *III* to *IV*.

Note.—Other Values For The Specific Heat Of A Gas May Be Found When The Pressure And Volume Of The Gas Both Vary during a change. Thus, if the gas is permitted to do external work at the same rate as that at which heat is added to it, Fig. 261, then the

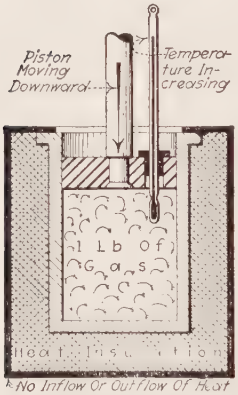


Fig. 263.—Specific heat is zero when a gas is compressed without loss or gain of heat (adiabatic compression).

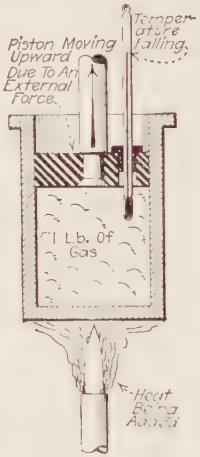


Fig. 264.—When a gas is heated and expanded simultaneously at such rates that the temperature is decreased, the specific heat is negative.

temperature remains constant in spite of the addition of heat (see example under Sec. 259). In such a case the specific heat is infinite for, no matter how much heat is added, the temperature does not rise. (See also Fig. 262.) Furthermore, if a gas is compressed while no heat is added or abstracted from it, Fig. 263, then its temperature will rise. Thus, no heat is required to effect the temperature rise and the specific heat is zero. Furthermore, a gas may be heated and expanded at such rates (Fig. 264) that its temperature actually decreases. In such a case more work is done than the equivalent of the heat energy added to the gas; the specific heat is negative because the temperature decreases in spite of a heat addition. So it is evident that the specific heat of a gas may have any value whatsoever.

268. The Energy Relations During Condition Changes Of Perfect Gases will now be considered. These energy rela-

tions are important principally in the study of gas cycles (Div. 12) for, as will be shown, all gas cycles are made up of a number of condition changes. The condition changes which gases undergo in actual gas cycles are principally those during which the specific heat of the gas has a constant value. Although condition changes are frequently spoken of as *expansions* and *compressions*, there is one form of condition change which is neither an expansion nor a compression—that is, the *constant-volume change*. Hence, the terms expansion and contraction should only be used for such condition changes during which the volume of the gas is actually changed.

Note.—Condition Changes May Occur In Any Manner—in an infinite number of ways. The condition changes of which gas cycles are considered as being ideally composed (Div. 12) are, however, such as occur when some property of the gas, such as its volume, pressure, temperature, or specific heat remains constant, or when no heat is transferred to or from the gas. As will be shown, in all of these cases the specific heat may be considered as having some constant value during the change—different for each change. Hence, broadly, the changes here discussed are all constant-specific-heat changes. Furthermore, during the changes here treated all of the volume of the gas is to be considered as being at the same pressure and temperature, as would occur when the gas is confined in a cylinder whose volume is varied by a movable piston. *Changes which a gas undergoes when a portion of it exists at a higher pressure or temperature than some other portion*, do not follow the laws here given. Such changes would occur when a gas is partly confined in one vessel at a high pressure and the remainder is in another vessel at a lower pressure, the two vessels being connected by a small opening through which the gas is flowing. In such a case there is always more or less throttling (note under Sec. 260) or internal friction in the gas —the following discussion does not apply to such frictional processes. Changes which occur in heat-engine cylinders are always practically "frictionless;" that is, they occur with practically no internal friction.

Note.—The Algebraic Signs Of Energy Quantities For Gases Will Be Determined Thus: (1) *Heat* (Q) is considered positive when it is added to a gas; negative when it is abstracted from the gas. (2) *External work* (W_E) is considered positive when the gas expands; negative when the gas is compressed—when external work is done *on* the gas. (3) *Vibration work* (W_V) is considered positive when the temperature of the gas is raised; negative when the temperature of the gas is lowered.

269. The Energy Relations During A Condition Change At Constant Volume—An Isometric Change—are quite simple. By the definition of specific heat at constant volume (Sec. 266)

the heat exchange to or from the gas is the product of the weight, temperature change, and specific heat at constant volume of the gas—see For. (175) below. Now, since during a constant-volume change no external work is done (Fig. 258), all of the heat added to or abstracted from the gas is effective in changing the temperature of the gas—that is, in doing vibration work. The formulas for these relations are:

$$\mathbf{Q} = \mathbf{W}\mathbf{C}_V(T_2 - T_1) \qquad \text{(B.t.u.)} \tag{175}$$

$$W_E = 0 \qquad \text{(external work)} \tag{176}$$

By multiplying For. (175) by "778," which is the number of foot-pounds in 1 B.t.u., there results:

$$W_V = 778\mathbf{W}\mathbf{C}_V(T_2 - T_1) \qquad \text{(foot-pounds)} \tag{177}$$

Wherein: $\mathbf{Q}$ = the heat added to the gas, in British thermal units. $\mathbf{W}$ = the weight of the gas, in pounds. $\mathbf{C}_V$ = the specific heat of the gas at constant volume; see Table 251. T_2 and T_1 = respectively, the final and initial temperatures of the gas in degrees Fahrenheit. W_E = the external work done by the gas. W_V = the vibration work done by the gas, in foot-pounds. See notes under Sec. 268 concerning the algebraic signs of the energy quantities and also as to the manner in which the changes are assumed to occur.

NOTE.—PRACTICAL EXAMPLES OF ISOMETRIC CHANGES may be stated thus: (1) *The heating or cooling of a given weight of gas which is enclosed in a strong tank or receiver.* (2) *The heating (explosion) of a gaseous mixture in an internal-combustion-engine* (Otto-cycle, Div. 12) *cylinder;* this process actually differs slightly from a strict isometric change because it is accompanied by a change in chemical composition of the gas—but it is often considered as an isometric condition change, see example below. The volume of the gases in the cylinder remains practically constant during the very short time interval occupied by the explosion.

EXAMPLE.—Suppose that an internal-combustion-engine cylinder contains $\frac{1}{5}$ lb. of gas at 120° F. and that this gas is ignited by an electric spark. What will be the final temperature if 65.8 B.t.u. are liberated by the explosion and if $\mathbf{C}_V$ for the mixture remains approximately 0.175 throughout the process? SOLUTION.—By transposing For. (175), there results: $T_2 = (\mathbf{Q}/\mathbf{W}\mathbf{C}_V) + T_1 = [65.8 \div (0.2 \times 0.175)] + 120 = 2{,}000°\ F.$

EXAMPLE.—If 1 lb. of a perfect gas is heated at constant volume through 1° F., Fig. 265, and if the specific heat of the gas at constant volume is 0.30, what quantity of heat is added, and what amounts of

external work and work in raising the temperature (vibration work) are done? SOLUTION.—By For. (175), the *heat added* = $Q = WC_V(T_2 - T_1) = 1 \times 0.30 \times 1 = 0.30$ *B.t.u.* By For. (176), the *external work* = $W_E = 0$. By For. (177), the *vibration work* = $W_V = 778WC_V(T_2 - T_1) = 778 \times 0.30 = 233.4$ *ft.-lb.*

EXAMPLE.—How much heat is added to 8 lb. of oxygen contained in a strong tank in raising its temperature from 70° F. to 500° F. (the volume of gas kept constant during the heating)? How much external work is done and how much work in raising the temperature (vibration work)? SOLUTION.—From Table 251, C_V for oxygen is 0.155. Hence, by For. (175), the *heat added* = $Q = WC_V(T_2 - T_1) = 8 \times 0.155(500 - 70) = 533.2$ *B.t.u.* By For. (176), the *external work* = $W_E = 0$. By For. (177), the vibration work = $W_V = 778WC_V(T_2 - T_1) = 778 \times 533.2 = 414{,}829.6$ *ft.-lb.*

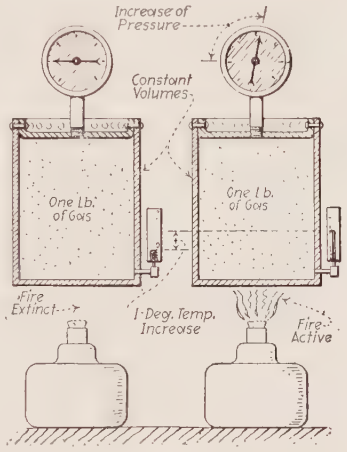


FIG. 265.—Specific heat at constant volume is 0.30. What are the energy relations?

270. The Energy Relations During A Condition Change At Constant Pressure—An Isobaric Change—are given by the following formulas which are derived as shown below:

(178) $$Q = WC_P(T_2 - T_1) \quad \text{(B.t.u.)}$$

(179) $$W_E = P(V_2 - V_1) \quad \text{(ft.-lb.)}$$

or

(180) $$W_E = 778W(C_P - C_V)(T_2 - T_1) \quad \text{(ft.-lb.)}$$

(181) $$W_E = Wk_0(T_2 - T_1) \quad \text{(ft.-lb.)}$$

(182) $$W_V = 778WC_V(T_2 - T_1) \quad \text{(ft.-lb.)}$$

Wherein: Q = the heat added to the gas, in British thermal units. W = the weight of the gas, in pounds. T_2 and T_1 = respectively, the final and initial temperatures of the gas, in degrees Fahrenheit. W_E = the external work done by the gas, in foot-pounds. P = the pressure exerted by the gas during the change, in pounds per square *foot* absolute. V_2 and V_1 = respectively, the final and initial volumes of the gas, in cubic feet. C_p and C_V = respectively, the specific

heats of the gas at constant pressure and at constant volume; for values see Table 251. k_G = the gas constant (Sec. 247). W_V = the vibration work done on the gas, in foot-pounds. See the notes under Sec. 268 regarding the algebraic signs of the energy quantities and also as to the manner in which the changes are assumed to occur.

Derivation.—By the definition of the specific heat at constant pressure (Sec. 267), the quantity of heat added to the gas is as shown by For. (178). Also, by Sec. 263, the work done during a constant-pressure expansion is equal to the pressure times the volume change—as shown by For. (179). Now, the vibration work done on a gas depends only on its weight and temperature change. Hence, for a given weight of any gas, when heated through a given temperature range, the vibration work will be the same regardless of how the pressure and volume vary. Therefore, *the vibration work for all condition changes*, is as given by For. (177) which is the same as For. (182). Since, for a perfect gas, the heat added is effective in doing only vibration and external work (Sec. 259),

(183) $$778\mathbf{Q} = W_V + W_E \qquad \text{(ft.-lb.)}$$

or, transposing:

(184) $$W_E = 778\mathbf{Q} - W_V \qquad \text{(ft.-lb.)}$$

Now, substituting in For. (184) from Fors. (178) and (182), there results

(185) $$W_E = 778\mathbf{W}\mathbf{C}_P(T_2 - T_1) - 778\mathbf{W}\mathbf{C}_V(T_2 - T_1) \qquad \text{(ft.-lb.)}$$

which simplifies to the form of For. (180).

By the general gas law, For. (145), $PV_1 = \mathbf{W}k_G\mathbf{T}_1$ and $PV_2 = \mathbf{W}k_G\mathbf{T}_2$. Also, For. (179), when expanded becomes:

(186) $$W_E = PV_2 - PV_1 \qquad \text{(ft.-lb.)}$$

Now, substituting in For. (186), the values from For. (145), there results,

(187) $$W_E = \mathbf{W}k_G\mathbf{T}_2 - \mathbf{W}k_G\mathbf{T}_1 \qquad \text{(ft.-lb.)}$$

or, simplifying:

(188) $$W_E = \mathbf{W}k_G(\mathbf{T}_2 - \mathbf{T}_1) \qquad \text{(ft.-lb.)}$$

But, it is a fact that:

(189) $$\mathbf{T}_2 - \mathbf{T}_1 = T_2 - T_1 \qquad \text{(deg. fahr.)}$$

Hence,

(190) $$W_E = \mathbf{W}k_G(T_2 - T_1) \qquad \text{(ft.-lb.)}$$

which is the same as For. (181).

Note.—Practical Applications Of Isobaric Changes are: (1) *The heating or cooling of a gas which is under constant pressure such as atmospheric pressure and which is not wholly confined*—as, for example, the gas in a balloon, the combustion gases in a boiler furnace, or the air which cools an automobile radiator. (2) *The expansion in an oil engine while*

the charge of oil is burned in the cylinder as the piston moves in the cylinder—this expansion is only sometimes isobaric, it may be quite different; this is not strictly a condition change because it is accompanied by a chemical change in the gases.

EXAMPLE.—How much heat is added to each 100 lb. of air which passes through a boiler furnace as its temperature is increased from 70° F. to 500° F.? SOLUTION.—By Table 251, for air, $C_P = 0.241$. Hence, by For. (178), the *heat added* $= Q = WC_P(T_2 - T_1) = 100 \times 0.241 \times (500 - 70) = 10{,}350$ *B.t.u.*

EXAMPLE.—How much heat must be added to 5 lb. of nitrogen to increase its volume from 45 cu. ft. to 100 cu. ft. at the constant pressure of 25 lb. per sq. in. abs.? How much external work is done by the expanding gas and how much (vibration) work is done in raising the temperature? SOLUTION.—For nitrogen, the value of k_G is, by Table 251, 54.99. Also, $C_P = 0.247$ and $C_V = 0.176$. The *initial temperature* of the gas is, by For. (148), $T_1 = PV_1/Wk_G = (25 \times 144) \times 45 \div (5 \times 54.99) = 498°$ *F. abs.* or 38° *F.* The *final temperature* $= T_2 = (25 \times 144) \times 100 \div (5 \times 54.99) = 1{,}309°$ *F. abs.* or 849° *F.* Hence, by For. (178), the *heat added* $= WC_P(T_2 - T_1) = 5 \times 0.247(849 - 38) = 1001.6$ *B.t.u.* By For. (179), the *external work* $= W_E = P(V_2 - V_1) = (25 \times 144)(100 - 45) = 198{,}000$ *ft.-lb.* By For. (182), $W_V = 778WC_V(T_2 - T_1) = 778 \times 5 \times 0.176(849 - 38) = 555{,}243$ *ft.-lb.*

EXAMPLE.—If 3 lb. of oxygen is expanded at constant pressure by increasing the temperature from 85° F. to 100° F. (Figs. 266 and 267), find how much heat is added, how much external work

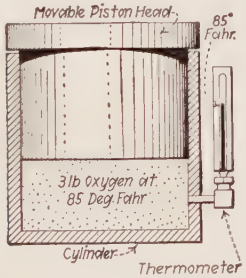


FIG. 266.—Oxygen gas (3 lb. at 85° F.) ready to be expanded under constant pressure.

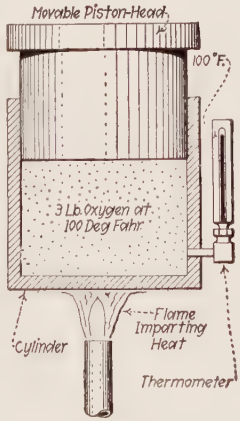


FIG. 267.—Conditions after the expansion of 3 lb. of oxygen gas under constant pressure by heating from 85° F. to 100° F.

is done, and how much (vibration) work is done in raising the temperature. SOLUTION.— From Table 251, the following values are found for oxygen: $C_P = 0.217$. $C_V = 0.155$. $k_G = 48.25$. Hence, by For. (178), the *heat added* $= Q = WC_P(T_2 - T_1) = 3 \times 0.217 \times (100 - 85) =$

9.765 *B.t.u.* Also, by For. (181), the *external work* $= W_E = \mathbf{W}k_G(T_2 - T_1) = 3 \times 48.25 \times (100 - 85) = 2{,}171.25$ *ft.-lb.* And, by For. (182), the *vibration work* $= W_V = 778\mathbf{W}C_V(T_2 - T_1) = 778 \times 3 \times 0.155 \times (100 - 85) = 5{,}426.55$ *ft.-lb.*

Example.—Assume that 10 cu. ft. of a certain gas at 32° F. exerts a pressure of 10 lb. per sq. ft. abs. (Fig. 268). Compare the external work done in expanding the gas at constant pressure to 15 cu. ft. with that done by compressing the gas at constant pressure to 5 cu. ft. Solution.—In expanding the gas, by For. (179), the *external work* $= W_E = P(V_2 - V_1) = 10(15 - 10) = 50$ *ft.-lb.* In compressing the gas, the *external work* $= W_E = P(V_2 - V_1) = 10(5 - 10) = -50$ *ft.-lb.* The negative sign indicates that work is done *on* the gas. Thus, *numerically* the same amount of work is done in the two cases—as is shown by the equal areas *A* and *B* in Fig. 268.

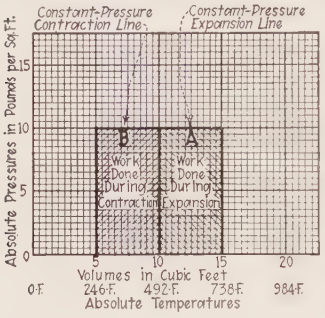


Fig. 268.—Work diagram showing constant-pressure expansion and contraction (10 cu. ft. of gas at 10 lb. per sq. ft. absolute, and 492° F. absolute = 15 cu. ft. of gas at 10 lb. per sq. ft. absolute, and 738° F. absolute = 5 cu. ft. of gas at 10 lb. per sq. ft. absolute, and 246° F. absolute).

271. The Energy Relations During A Condition Change At Constant Temperature—An Isothermal Change—may be found by the following formulas which are derived as shown below. The pressure-volume relations for an isothermal change are governed by Boyle's law, For. (108).

$$W_E = P_1V_1 \log_e \frac{V_2}{V_1} \quad \text{(ft.-lb.)} \tag{191}$$

$$W_E = P_1V_1 \log_e \frac{P_1}{P_2} \quad \text{(ft.-lb.)} \tag{192}$$

$$W_E = \mathbf{W}k_G\mathbf{T} \log_e \frac{V_2}{V_1} \quad \text{(ft.-lb.)} \tag{193}$$

$$\mathbf{Q} = \frac{W_E}{778} \quad \text{(B.t.u.)} \tag{194}$$

$$W_V = 0 \quad \text{(work)} \tag{195}$$

Wherein: $\mathbf{Q}$ = the heat added to the gas, in British thermal units. P_1 and P_2 = respectively, the initial and final pressures of the gas, in pounds per square foot absolute. V_1 and V_2 = respectively, the initial and final volumes of the gas, in cubic

feet. $\mathbf{W}$ = the weight of the gas, in pounds. k_G = the gas constant (Sec. 247). $\mathbf{T}$ = the temperature of the gas, in degrees Fahrenheit *absolute*. W_E = the external work done by the gas, in foot-pounds. W_V = the vibration work done on the gas. Log_e = the natural logarithm of the number following the symbol. The natural logarithm of a number is approximately 2.303 times the common logarithm of the same number. See the notes under Sec. 268 regarding the algebraic signs of the energy quantities and also as to the manner in which the changes are assumed to occur.

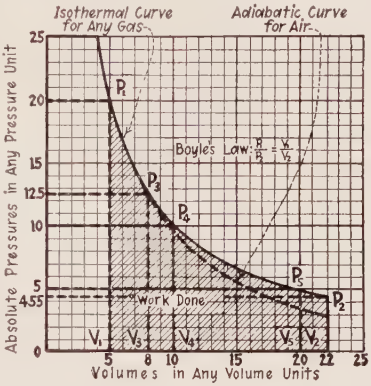


Fig. 269.—Isothermal or constant-temperature expansion graph.

Derivation.—Since, during an isothermal change, the temperature remains constant, none of the heat added is effective in doing vibration work. This may also be shown by placing $T_2 = T_1$ in For. (177) which, as has been stated, applies to *any* condition change. This relation is stated by For. (195). Now, For. (166) states that, for any heat transfer:

$$\mathbf{Q} = Q_V + Q_D + Q_E \qquad \text{(B.t.u.)} \tag{196}$$

Hence, since for a perfect gas $Q_D = 0$ (as proved under Sec. 258) and since for an isothermal change $Q_V = 0$, For. (196) becomes:

$$\mathbf{Q} = Q_E \qquad \text{(B.t.u.)} \tag{197}$$

and, since $Q_E = W_E/778$:

$$\mathbf{Q} = \frac{W_E}{778} \qquad \text{(B.t.u.)} \tag{198}$$

which is the same as For. (194).

Now, the pressure-volume graph of an isothermal change is a curved line (Fig. 269). For a change from P_1, V_1 to P_2, V_2, the area under the graph (the shaded area in Fig. 269) is found by the calculus to be expressed by the formula:

$$Area = P_1 V_1 \log_e \frac{V_2}{V_1} \qquad \text{(area units)} \tag{199}$$

If, now, the pressures are expressed in pounds per square foot and the volumes in cubic feet, the area will represent the work done, in foot-pounds, as expressed by For. (191).

For. (192) results from For. (191) by substituting for V_2/V_1 its equivalent from For. (108). For. (193) results from For. (191) by substituting

for P_1V_1 its equivalent from For. (145). These substitutions may suggest to the reader still different ways of expressing For. (191).

NOTE.—THERE ARE NO PRACTICAL APPLICATIONS OF ISOTHERMAL GAS CHANGES.—The nearest approach to such a change would probably occur in an air compressor. In this machine water, which is circulated through a jacket surrounding the cylinder, carries away a large part of the heat which is developed by the work done on the air in compressing it. Isothermal changes are of value, however, because they constitute the *ideal compression* for air and other gas compressors and hence afford a goal in compressor design.

EXAMPLE.—If a certain gas exerts a pressure of 100 lb. per sq. ft. abs. when confined in a volume of 5 cu. ft. and is expanded isothermally to a volume of 22 cu. ft., how much external work is done and how much heat must have been added during the process? SOLUTION.—By For. (191), the *external work* $= W_E = P_1V_1 \log_e(V_2/V_1) = 100 \times 5 \times \log_e(22 \div 5) = 500 \times \log_e 4.4$. From tables of logarithms, the *common logarithm* of $4.4 = \log 4.4 = 0.643$. Hence, $\log_e 4.4 = 2.303 \times 0.643 = 1.479$. Hence, $W_E = 500 \times 1.479 = 739.5$ *ft.-lb.* By For. (194), the *heat added* $= Q = W_E/778 = 739.5 \div 778 = 0.95$ *B.t.u.*

EXAMPLE.—How much external work is done when 6 lb. of hydrogen is compressed at the constant temperature of 70° F. from a volume of 144 cu. ft. to a final volume of 12 cu. ft.? How much heat must be abstracted? SOLUTION.—By Table 251, for hydrogen, $k_G = 765.9$. By For. (193), the *external work* $= W_E = Wk_G \log_e(V_2/V_1) = 6 \times 765.9 \times \log_e(12 \div 144) = 4{,}595.4 \times \log_e(1/12)$. From a table of logarithms the *common logarithm* of $1/12 = \log(1/12) = -1.079$. Hence $\log_e(1/12) = 2.303 \times (-1.079) = -2.482$. Hence, $W_E = 4{,}595.4 \times (-2.482) = -11{,}406$ *ft.-lb.* Hence, 11,406 ft.-lb. of work must be done *on* the gas. By For. (194), the *heat added* $= Q = W_E/778 = -11{,}406 \div 778 = -14.66$ *B.t.u.* Hence, 14.66 B.t.u. must be *abstracted.*

272. The Energy Relations During A Condition Change Which Involves No Heat Transfer—A Frictionless Adiabatic Change (which is the same as an isentropic change, Sec. 385), (Figs. 270 and 271)—may be found by the following formulæ which are derived below. The pressure-volume relations for and adiabatic change (Sec. 275) are based on these energy relations.

(200) $$Q = 0 \qquad \text{(heat)}$$

(201) $$W_E = \frac{P_1V_1 - P_2V_2}{k - 1} \qquad \text{(ft.-lb.)}$$

(202) $$W_E = 778WC_V(T_1 - T_2) \qquad \text{(ft.-lb.)}$$

(203) $$W_V = -W_E \qquad \text{(ft.-lb.)}$$

(204) $$W_V = 778WC_V(T_2 - T_1) \qquad \text{(ft.-lb.)}$$

Wherein: $\mathbf{Q}$ = the heat added during the change. W_E = the external work done by the gas, in foot-pounds. P_1 and P_2 = respectively, the initial and final pressures exerted by the gas,

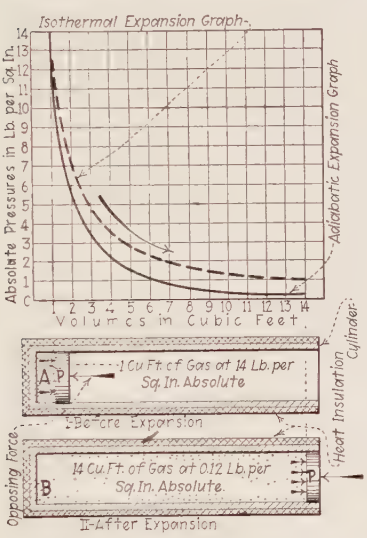

Isothermal Expansion Graph
Absolute Pressures in Lb. per Sq. In.
Volumes in Cubic Feet.
Adiabatic Expansion Graph
Cylinder
Heat Insulation
1 Cu. Ft. of Gas at 14 Lb. per Sq. In. Absolute
I-Before Expansion
14 Cu. Ft. of Gas at 0.12 Lb. per Sq. In. Absolute.
Opposing Force
II-After Expansion

FIG. 270.—Adiabatic gas expansion—when heat can neither enter nor leave the gas through the confining surfaces.

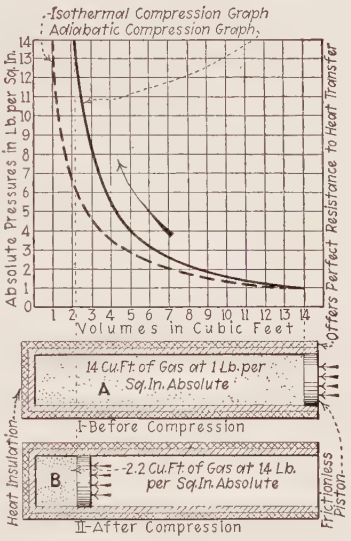

Isothermal Compression Graph
Adiabatic Compression Graph
Absolute Pressures in Lb. per Sq. In.
Volumes in Cubic Feet
Offers Perfect Resistance to Heat Transfer
14 Cu. Ft. of Gas at 1 Lb. per Sq. In. Absolute
I-Before Compression
Heat Insulation
2.2 Cu. Ft. of Gas at 14 Lb. per Sq. In. Absolute
Frictionless Piston
II-After Compression

FIG. 271.—Adiabatic gas compression—when heat can neither enter nor leave the gas, as heat, through the confining surfaces.

in pounds per square foot absolute. V_1 and V_2 = respectively, the initial and final volumes of the gas, in cubic feet. $\mathbf{k}$ = the ratio ($\mathbf{C}_P/\mathbf{C}_V$) of the specific heats of the gas at constant pressure and constant volume; values of $\mathbf{k}$ are given in Table 251. $\mathbf{C}_V$ = the specific heat of the gas at constant volume; Table 251. T_1 and T_2 = respectively, the initial and final temperatures of the gas, in degrees Fahrenheit. W_V = the vibration work done on the gas, in foot-pounds. See notes under Sec. 268 concerning the algebraic signs of the energy quantities, and concerning frictional processes.

DERIVATION.—By the definition of an adiabatic process, there is no heat transfer between the gas and any external body. This statement is stated algebraically by For. (200). Also, For. (204) has been shown (Sec. 270) to hold for *any* condition change. Now, substituting in For. (196), the values $\mathbf{Q} = 0$, and $\mathbf{Q}_D = 0$, there results:

(205) $$\mathbf{Q}_E = -\mathbf{Q}_V \qquad \text{(B.t.u.)}$$

Hence, it follows that:

$$W_E = -W_V \quad \text{(ft.-lb.)} \tag{206}$$

which is the same as For. (203). Substituting in For. (206) the value of W_V from For. (204), there results For. (202).

By For. (145) transposed,

$$\mathbf{WT}_1 = \frac{P_1V_1}{k_G} \tag{207}$$

and

$$\mathbf{WT}_2 = \frac{P_2V_2}{k_G} \tag{208}$$

Now, For. (202) may be written thus:

$$W_E = 778\mathbf{C}_V(\mathbf{WT}_1 - \mathbf{WT}_2) \quad \text{(ft.-lb.)} \tag{209}$$

Which becomes, by substituting from Fors. (207) and (208):

$$W_E = \frac{778\mathbf{C}_V}{k_G}(P_1V_1 - P_2V_2) \quad \text{(ft.-lb.)} \tag{210}$$

Now, by comparing Fors. (180) and (181), it is evident that

$$k_G = 778(\mathbf{C}_P - \mathbf{C}_V) \tag{211}$$

Hence,

$$\frac{778}{k_G} = \frac{1}{\mathbf{C}_P - \mathbf{C}_V} \tag{212}$$

Or, by multiplying For. (212) by $\mathbf{C}_V$

$$\frac{778\mathbf{C}_V}{k_G} = \frac{\mathbf{C}_V}{\mathbf{C}_P - \mathbf{C}_V} \tag{213}$$

or,

$$\frac{778\mathbf{C}_V}{k_G} = \frac{1}{\frac{\mathbf{C}_P}{\mathbf{C}_V} - 1} \tag{214}$$

If the fraction $\frac{\mathbf{C}_P}{\mathbf{C}_V}$ is denoted by k, then For. (214) becomes:

$$\frac{778\mathbf{C}_V}{k_G} = \frac{1}{\mathbf{k} - 1} \tag{215}$$

Substituting this in For. (210), there results:

$$W_E = \frac{1}{\mathbf{k} - 1}(P_1V_1 - P_2V_2) \quad \text{(ft.-lb.)} \tag{216}$$

which is the same as For. (201).

NOTE.—OCCURRENCES OF ADIABATIC CHANGES IN PRACTICE are, strictly speaking, never found. Quite close approaches to adiabatic processes are, however, found in: (1) *Internal-combustion engines.* (2) *Air and other gas compressors;* the compressions in these machines are generally more nearly adiabatic than they are isothermal, Sec. 271. (3) *Compressed-air engines.* Adiabatic expansions are the *ideal* expansions (see Div. 12) for heat engines.

Example.—How much work is done by carbon-monoxide gas in expanding adiabatically from a pressure of 100 lb. per sq. in. abs. and a volume of 5 cu. ft. to a pressure of 20 lb. per sq. in. abs. and a volume of 15.6 cu. ft.? Solution.—By Table 251, the value of k_G for carbon monoxide is 1.41. Hence, by For. (201), the *external work* $= W_E = (P_1V_1 - P_2V_2)/\mathbf{k} - 1 = [(144 \times 100 \times 5) - (144 \times 20 \times 15.6)] \div (1.41 - 1) = (72{,}000 - 44{,}920) \div 0.41 = 65{,}270$ *ft.-lb.*

Example.—How much work is done in compressing 7 lb. of acetylene adiabatically from 70° F. to 300° F.? Solution.—By Table 251, the value of C_V for acetylene is 0.270. Hence, by For. (202), the *external work* $= W_E = 778\mathbf{W}C_V(T_1 - T_2) = 778 \times 7 \times 0.270 \times (70 - 300) = -374{,}530$ *ft.-lb.* Or, 374,530 ft.-lb. must be *expended* in compressing the gas.

273. The Energy Relations, Accompanying A Condition Change During Which The Specific Heat Has Any Constant Value—A Polytropic Change—may be found by the following formulas which are derived below. The pressure-volume relations for a polytropic change (Sec. 275) are based on these relations.

(217) $$\mathbf{Q} = \mathbf{W}\mathbf{C}(T_2 - T_1) \qquad \text{(B.t.u.)}$$

(218) $$W_E = \frac{P_1V_1 - P_2V_2}{n - 1} \qquad \text{(ft.-lb.)}$$

(219) $$W_E = 778\mathbf{W}(\mathbf{C} - \mathbf{C}_V)(T_2 - T_1) \qquad \text{(ft.-lb.)}$$

(220) $$W_V = 778\mathbf{W}\mathbf{C}_V(T_2 - T_1) \qquad \text{(ft.-lb.)}$$

Where,

(221) $$n = \frac{\mathbf{C} - \mathbf{C}_P}{\mathbf{C} - \mathbf{C}_V} \qquad \text{(a constant)}$$

(222) $$\mathbf{C} = \frac{n - \mathbf{k}}{n - 1}\mathbf{C}_V \qquad \text{(specific heat)}$$

Wherein: $\mathbf{Q}$ = the heat added to the gas, in British thermal units. $\mathbf{W}$ = the weight of the gas, in pounds. $\mathbf{C}$ = the specific heat of the gas during the process. T_1 and T_2 = respectively, the initial and final temperatures of the gas, in degrees Fahrenheit. P_1 and P_2 = respectively, the initial and final pressures of the gas, in pounds per square foot absolute. V_1 and V_2 = respectively, the initial and final volumes of the gas, in cubic feet. W_E = the external work done by the gas, in foot-pounds. W_V = the vibration work done on the

gas, in foot-pounds. n = a constant defined by For. (221). $\mathbf{C}_P$ and $\mathbf{C}_V$ = respectively the specific heats of the gas at constant pressure and constant volume. $\mathbf{k}$ = the ratio $\mathbf{C}_P/\mathbf{C}_V$. See notes under Sec. 268 concerning the algebraic signs of the energy quantities and also as to the manner in which the changes are assumed to occur.

DERIVATION.—The specific heat ($\mathbf{C}$) is, by definition (Sec. 88), the number of British thermal units which must be added to 1 lb. of a substance in order to raise its temperature through 1° F. Hence, to raise the temperature of W lb. of gas through $(T_2 - T_1)$° F., there must be added $\mathbf{WC}(T_2 - T_1)$ B.t.u. as expressed by For. (217). Also, For. (220) expresses the quantity of vibration work done during *any* condition change. By Sec. 259, the added heat is always effective only in doing vibration work and external work. Hence,

$$W_E = 778\mathbf{Q} - W_V \qquad \text{(ft.-lb.)} \tag{223}$$

Or, substituting from Fors. (217) and (220) and simplifying, there results:

$$W_E = 778\mathbf{W}(\mathbf{C} - \mathbf{C}_V)(T_2 - T_1) \qquad \text{(ft.-lb.)} \tag{224}$$

which is the same as For. 219. This For. (224) may also be written:

$$W_E = 778\mathbf{W}(\mathbf{C}_V - \mathbf{C})(T_1 - T_2) \qquad \text{(ft.-lb.)} \tag{225}$$

or,

$$W_E = 778(\mathbf{C}_V - \mathbf{C})(\mathbf{W}T_1 - \mathbf{W}T_2) \qquad \text{(ft.-lb.)} \tag{226}$$

But, substituting from Fors. (207) and (208),

$$W_E = \frac{778(\mathbf{C}_V - \mathbf{C})}{k_G}(P_1V_1 - P_2V_2) \qquad \text{(ft.-lb.)} \tag{227}$$

Now, since $\mathbf{k} = \mathbf{C}_P \div \mathbf{C}_V$, For. 222 may be written:

$$\mathbf{C} = \frac{n\mathbf{C}_V - \mathbf{C}_P}{n - 1} \tag{228}$$

Or, subtracting both sides from $\mathbf{C}_V$,

$$\mathbf{C}_V - \mathbf{C} = \frac{\mathbf{C}_P - \mathbf{C}_V}{n - 1} \tag{229}$$

Also, by For. (211),

$$k_G = 778(\mathbf{C}_P - \mathbf{C}_V) \tag{230}$$

Therefore, by substituting Fors. (229) and (230) into For. (227) there results:

$$W_E = \frac{P_1V_1 - P_2V_2}{n - 1} \qquad \text{(ft.-lb.)} \tag{231}$$

which is the same as For. (218).

NOTE.—OCCURRENCES OF POLYTROPIC CHANGES IN PRACTICE are many. In practically all reciprocating machines, wherein gases are employed,

the expansions and compressions of the gases are, for all practical purposes, polytropic. Actually, the specific heat probably varies somewhat during all gas expansions and compressions but, because of the short time interval which is generally consumed in one of these processes, the variation in any case is quite small.

EXAMPLE.—If 1.5 lb. of hydrogen is compressed polytropically from 15 lb. per sq. in. abs. to 500 lb. per sq. in. abs. at which pressures its volumes are 200 cu. ft. and 10.76 cu. ft. respectively, how much heat is added, external work done, and vibration work? The value of n is 1.2. SOLUTION.—For hydrogen, by Table 251, $\mathbf{C}_V = 2.44$, $k_G = 765.9$, and $\mathbf{k} = 1.40$. By For. (222), the *specific heat* $= \mathbf{C} = [(n - \mathbf{k})/(n - 1)] \times \mathbf{C}_V = [(1.2 - 1.40) \div (1.2 - 1)] \times 2.44 = (-0.20 \div 0.2) \times 2.44 = -2.44$. Hence, by For. (218), the *external work* $= W_E = (P_1V_1 - P_2V_2)/(n - 1) = [(15 \times 144 \times 200) - (500 \times 144 \times 10.76)] \div (1.2 - 1) = (432{,}000 - 774{,}720) \div 0.2 = -1{,}713{,}600$ *ft.-lb.* By For. (148), $\mathbf{T}_1 = P_1V_1/\mathbf{W}k_G = (144 \times 15 \times 200) \div (1.5 \times 765.9) = 376°$ *F. abs.* Also, $\mathbf{T}_2 = P_2V_2/\mathbf{W}k_G = (144 \times 500 \times 10.76) \div (1.5 \times 765.9) = 764.3°$ *F. abs.* Hence, by For. (217), the *heat added* $= \mathbf{WC}(T_2 - T_1) = 1.5 \times (-2.44) \times (764.3 - 376) = -1{,}420.01$ *B.t.u.* and, by For. (220), the *vibration work* $= W_V = 778\mathbf{WC}_V(T_2 - T_1) = 778 \times 1.5 \times 2.44 \times (764.3 - 376) = 1{,}105{,}676$ *ft.-lb.*

EXAMPLE.—If, in an air engine, 7 lb. of air expand in such a manner that $n = 1.1$ and the temperature is reduced from 100° F. to 40° F., how much heat is added or abstracted, how much external work is done, and how much (vibration) work in reducing the temperature? SOLUTION.—From Table 251, for air, $\mathbf{C}_P = 0.241$, $\mathbf{C}_V = 0.171$, and $\mathbf{k} = 1.40$. Hence, by For. (222), the *specific heat* $= \mathbf{C} = [(n - \mathbf{k})/(n - 1)]\ \mathbf{C}_V = [(1.1 - 1.40) \div (1.1 - 1)] \times 0.171 = -0.533$. Therefore, by For. (217) the *heat added* $= \mathbf{Q} = \mathbf{WC}(T_2 - T_1) = 7 \times (-0.533) \times (40 - 100) = 223.9$ *B.t.u.* Hence, 223.9 B.t.u. must be added. By For. (219), the *external work* $= W_E = 778\mathbf{W}(\mathbf{C} - \mathbf{C}_V)(T_2 - T_1) = 778 \times 7 \times (-0.533 - 0.171) \times (40 - 100) = 230{,}000$ *ft.-lb.* By For. (220), the *vibration work* $= W_V = 778\ \mathbf{WC}_V(T_2 - T_1) = 778 \times 7 \times 0.171 \times (40 - 100) = -55{,}900$ *ft.-lb.*

274. A Table Of Values Of The Polytropic Exponent n For Actual Machines is given below.—Since, by For. (221), n varies with the specific heat of the gas during a process, and since (Sec. 265) the specific heat may have any value whatsoever, it follows that n may also have any value whatsoever. In actual machines, however, the values of n generally have some value intermediate between 1 and $\mathbf{k}$—that is, the expansion or compression is intermediate between isothermal and adiabatic depending on the design and operation of the machine. The following values have been determined by experiment:

Type of machine	Value of n	Authority
Air compressor—cooling by injection of water	1.26–1.36	Ennis—"Applied Thermodynamics"
Air compressor—cooling by water jacket	seldom below 1.30	Ennis—"Applied Thermodynamics"
Hydraulic piston air compressors	1.23–1.28	Ennis—"Applied Thermodynamics"
Gas engines expansion, large engines	1.25	Ennis—"Applied Thermodynamics"
Gas engines expansion, small engines	1.38	Ennis—"Applied Thermodynamics"
Gas engines expansion, occasionally as high as	1.55	Ennis—"Applied Thermodynamics"
Air compressors, water jacketed	1.25–1.35	Shealy—"Heat"
Air engines	1.3 –1.35	Shealy—"Heat"
Air compressors, average value	1.3	Marks—"Mechanical Engineers' H. B."
Gas engines, compression stroke	1.25–1.35	Marks—"Mechanical Engineers' H. B."
Gas engines, expansion stroke (generally)	1.30–1.50	Marks—"Mechanical Engineers' H. B."
Gas engines, expansion stroke sometimes	1.70	Marks—"Mechanical Engineers' H. B."

275. The Pressure-volume-temperature Relations For A Perfect Gas During Adiabatic Or Polytropic Processes may be found by the following formulas together with those of Sec. 249. As the derivation of the following formulas involves the calculus, the derivations will not be here given. See notes under Secs. 272 and 273 for occurrences of adiabatic and polytropic expansions in practice. The formulas are:

(232) $$PV^n = K \qquad \text{(constant)}$$

(233) $$P_1V_1^n = P_2V_2^n$$

(234) $$P_2 = P_1\left(\frac{V_1}{V_2}\right)^n$$

(235) $$V_2 = V_1\left(\frac{P_1}{P_2}\right)^{\frac{1}{n}}$$

(236) $$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$$

(237) $$T_2 = T_1\left(\frac{V_1}{V_2}\right)^{n-1}$$

$$P_2 = P_1\left(\frac{\mathbf{T}_2}{\mathbf{T}_1}\right)^{\frac{n}{n-1}} \tag{238}$$

$$V_2 = V_1\left(\frac{\mathbf{T}_1}{\mathbf{T}_2}\right)^{\frac{1}{n-1}} \tag{239}$$

Wherein: P and V = respectively, the absolute pressure and volume of the gas at any point along the path, in any units. K = a constant. n = the polytropic exponent which is defined by For. (221); for adiabatic processes $n = \mathbf{k} = \mathbf{C}_P/\mathbf{C}_V$. P_1 and P_2 = respectively, the absolute pressure at a first and second instant during the condition change, in any units. V_1 and V_2 = respectively, the volumes of the gas at the same first and second instants during the condition change, in any units. $\mathbf{T}_1$ and $\mathbf{T}_2$ = respectively, the absolute temperatures of the gas at the same first and second instants during the condition change, in any units.

NOTE.—THE APPLICATION OF THE ABOVE FORMULAS GENERALLY INVOLVES THE USE OF LOGARITHMS.—Although Fors. (234) to (239) can frequently be solved readily by using special slide-rules, the use of logarithms is more common and will be used in the following examples. The problems should serve to explain the *method of solving problems involving fractional exponents.*

EXAMPLE.—Find the final pressure when air in an air engine is expanded adiabatically from a volume 1 cu. ft. at 115 lb. per sq. in. abs. to a final volume of 6 cu. ft. SOLUTION.—From Table 251, k for air = 1.40. Hence, by For. (234), the *final pressure* $= P_2 = P_1(V_1/V_2)^n = 115 \times (1 \div 6)^{1.40} = 115 \times (0.166{,}7)^{1.40}$. To find the value of $(0.166{,}7)^{1.40}$, first find the logarithm of 0.166,7. From a table of logarithms, log 0.166,7 = 9.221,9 − 10 = −0.778,1. Now multiply this value by the exponent, thus: 1.40 × −0.778,1 = − 1.089,3. Now, find the number of which this is the logarithm, thus: $\log^{-1} - 1.089{,}3 = \log^{-1} 8.910{,}7 - 10 = 0.081{,}42$. Hence, $(0.166{,}7)^{1.40} = 0.081{,}42$ and $P_2 = 115 \times 0.081{,}42 = 9.36$ *lb. per sq. in. abs.*

EXAMPLE.—In a gas engine, what will be the volume at 15 lb. per sq. in. abs. of a given quantity of gas after polytropic expansion ($n = 1.25$) from a volume of 2 cu. ft. at a pressure of 135 lb. per sq. in. abs.? SOLUTION.—By For. (235), the *final volume* $= V_2 = V_1(P_1/P_2)^{\frac{1}{n}} = 2 \times (135 \div 15)^{\frac{1}{1.25}} = 2 \times 9^{0.8}$. Now, $\log 9 = 0.954{,}2$. And, $0.8 \times 0.954{,}2 = 0.763{,}36 = \log 6.072$. Hence, $V_2 = 2 \times 6.072 = 12.144$ *cu. ft.*

Example.—If the initial temperature of the gas of the preceding example is 1,150° F., what will be its final temperature? Solution.—By For. (236), the *final temperature* $= \mathbf{T}_2 = \mathbf{T}_1(P_2/P_1)^{\frac{n-1}{n}} = (460 + 1{,}150) \times (15 \div 135)^{\frac{1.25-1}{1.25}} = 1{,}640 \times \frac{1}{9}^{0.20}$. Now, $\log \frac{1}{9} = 9.045{,}8 - 10 = -0.954{,}2$. And, $0.2 \times -0.954{,}2 = 0.190{,}84 = 9.809{,}16 - 10 = \log 0.644{,}4$. Hence, $T_2 = 1{,}640 \times 0.644{,}4 = 1{,}056°$ *F. abs.*, or 596° *F.*

276. Dalton's Law Of Gases (see discussion of this same subject in Sec. 306) states that *each separate gas, in a mixture of gases, responds to changes of pressure, volume, and temperature exactly as though it were entirely isolated from the other gases.* Therefore, if all of the gases in a gaseous mixture are such (which means not near their saturation temperature) that they obey, approximately, the laws of perfect gases (Sec. 226), then the mixture, as a whole, will follow, approximately, the laws of perfect gases.

Note.—If the pressure exerted by a gaseous mixture be more definitely analyzed, it will be found that each of the constituent gases therein has the same pressure that it would have if it existed alone. Therefore, the pressure of the mixture is the sum of the pressures of its constituent gases. This principle, which is sometimes called the *law of partial pressures*, is embodied in *Dalton's law.*

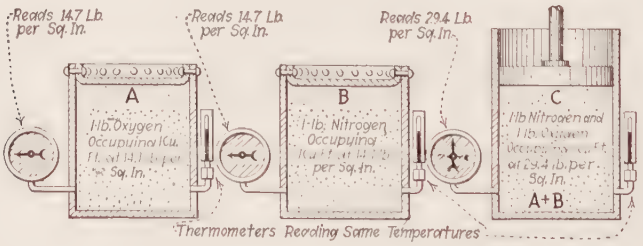

Reads 14.7 Lb. per Sq. In.
Reads 14.7 Lb. per Sq. In.
Reads 29.4 Lb. per Sq. In.
A
1 Lb. Oxygen Occupying 1 Cu. Ft. at 14.7 Lb. per Sq. In.
B
1 Lb. Nitrogen Occupying 1 Cu. Ft. at 14.7 Lb. per Sq. In.
C
1 Lb Nitrogen and 1 Lb. Oxygen Occupying 2 Cu. Ft. at 29.4 Lb. per Sq. In.
A+B
Thermometers Reading Same Temperatures

Fig. 272.—Illustrating Dalton's law.

Example.—If (Fig. 272) 1 cu. ft. of oxygen and 1 cu. ft. of nitrogen, at atmospheric pressure, were placed together in a vessel of 1 cu. ft. capacity, then the pressure of the mixture would, since *atmospheric pressure* = 14.7 *lb. per sq. in.*, be $14.7 \times 2 = 29.4$ *lb. per sq. in.*

QUESTIONS ON DIVISION 8

1. What is the practical importance of the heat phenomena of gases?

2. Define a *gas*. What is the distinction between a gas and a vapor?

3. What is a *perfect* gas? Has any perfect gas been found? Name some gases which behave nearly like a perfect gas.

4. What is meant by the *condition* of a gas? By what is it determined? What is a *condition change*?

5. What is meant by saying that a certain property of a gas is maintained constant, when working with the gas laws?

6. State Boyle's law. How was it discovered? For what kind of changes does it hold?

7. To what kind of problems may Boyle's law be applied?

8. Write Boyle's law as a formula expressing it in at least three different ways. What precautions must be taken with regard to the units?

9. If a given weight of a certain gas undergoes condition changes at constant temperature, what relation always holds between its pressure and volume?

10. For constant-volume changes, how does the pressure of a gas at any temperature compare with its pressure at 32° F.? State this as a formula.

11. For constant-pressure changes, how does the volume at any temperature compare with its volume at 32° F.? Does it matter what the pressure is during such a change? State the relationship as a formula.

12. According to the formulas for constant-volume and constant-pressure changes, what would be the pressure and volume of a perfect gas at −460° F.? What is this temperature called? State the conversion formulas for temperatures.

13. Give the verbal statement of Charles' law. For what kind of condition changes does it hold? Interpret the law.

14. To what kind of problems may Charles' law be applied? Does a heat exchange always accompany such changes?

15. Write Charles' law as a formula and express the formula in three different ways. What precautions must be taken as to the units in these formulas. Show that these formulas are the same as those given in answer to Question 10.

16. Give the verbal statement of Gay-Lussac's law. For what kind of condition changes does it hold? Cite simple examples to interpret the law.

17. To what kind of problems may Gay-Lussac's law be applied? Does a heat exchange always accompany such changes?

18. Write three expressions (as formulas) for Gay-Lussac's law. State the precautions which must be observed with regard to the units in which the quantities are measured.

19. Show how two of the three fundamental gas laws may be used to solve problems involving the simultaneous change of the volume, pressure, and temperature of a gas. For a given example how are the two laws selected?

20. State the formulas for the combined gas law. Show their derivation.

21. What is the constant relationship between the pressure, volume, and temperature of a given weight of a perfect gas as the gas undergoes condition changes? Express it by a formula.

22. In what units may the values of the gas properties (pressure, volume, and temperature) be expressed when they are used with the values of the gas constant as tabulated in this division? How are the gas-constant values determined?

23. Give a verbal statement of the general gas law. Why is it considered important? What is it based on?

24. Write the general-gas-law formula and the formulas which result from it. Show the derivation of the formula.

25. What two types of problems are, in general, solvable by the general gas law?

26. What is the engineering definition of density? What unit is widely used for measuring densities? State the formulas which show the interrelations between volume, weight, and density.

27. Is the density of gases a constant or variable quantity? Explain fully.

28. Write the equations which show the relation between the density of a gas and other properties of the gas.

29. Explain fully how air drafts may be caused by differences in density.

30. Wherein do the heat effects on gases differ from those on solids and liquids? Explain fully.

31. How much disgregation work is done when a perfect gas is heated? How was this determined? Make a sketch and explain the experiment.

32. What two effects may be produced when heat is added to a gas? Explain experiments, using sketches, to prove that these two effects are produced.

33. Explain fully how it is that a gas does external work when it expands. Draw a sketch to show how a gas does external work.

34. What is a *throttling expansion?* Explain what happens in such an expansion.

35. Explain fully, using sketches, how an area may be used to represent the work done by a constant force. A variable force. Does each area unit necessarily represent one force unit? Why?

36. What is the significance of the area under a pressure-volume graph? Explain fully, using sketches.

37. What is meant by *effective work? Total work?* What is the difference between these two called?

38. Is the specific heat of a gas a fairly well defined quantity like that of a solid or liquid? Why? Explain.

39. Explain the significance of the specific heat of a gas at constant volume. Draw a sketch to illustrate.

40. Is the specific heat of a gas at constant pressure greater or less than that at constant volume? Why? Does its value depend upon the pressure? How would you prove this?

41. May a gas have other specific heats than those just referred to? When?

42. Explain the significance of an infinite specific heat. A specific heat of zero. A negative specific heat.

43. Of what importance are the energy relations which accompany condition changes of gases? Why should condition changes not be spoken of as expansions and compressions?

44. How many different kinds of condition changes are there for gases? Of what definite kind are gas cycles composed?

45. Do the laws and formulas, of this division apply to expansions through orifices or nozzles? Why?

46. State the energy relations for a constant-volume change. How much external work is done? What becomes of the added heat?

47. Write the energy-relation formulas for a constant-pressure change Why must more heat be added for a given weight of gas and a given temperature increase than for a constant-volume change? Derive the formulas.

48. Write the energy relations for a constant-temperature change. What is such a change called? How are these relations derived?

49. What name is given to a condition change which involves no heat transfer? Is any external work done during such a change? Draw a sketch to show an ideal apparatus with which such a change might be effected.

50. Write and derive the energy relations for an adiabatic change.

51. What property of a gas remains constant during a polytropic change?

52. Write and derive the energy relations for a polytropic change.

53. State the pressure-volume relations for a perfect gas undergoing a polytropic change and explain the meanings of the symbols in the formula.

54. Explain the use of logarithms for solving equations involving fractional exponents.

PROBLEMS ON DIVISION 8

1. At 32° F. and atmospheric pressure (14.7 lb per sq. in. abs.) 1 lb. of air occupies 12.39 cu. ft. At the same temperature what pressure will it exert when confined in 2 cu. ft.?

2. Three cubic feet of air at atmospheric pressure are to be compressed at constant temperature to 100 lb. per sq. in. gage. What volume will the air then occupy?

3. If a given weight of gas at 32° F. exerts a pressure of 60 lb. per sq. in. abs., what pressure will it exert at 100° F. when in the same volume? Solve by For. (115).

4. Using For. (117) and the data of Prob. 1, find the volume of 1 lb. of air at atmospheric pressure and 70° F.

5. Using For. (121) and the data of Prob. 1 find the pressure exerted by 1 lb. of air when confined in 12.39 cu. ft. at 300 ° F.

6. A tank holds a certain volume of gas at 70° F. and 60 lb. per sq. in. gage pressure. To what temperature must the gas be heated so that the pressure shall be 100 lb. per sq. in. gage?

7. A given weight of gas at atmospheric pressure and 40° F. occupies 3 cu. ft. What volume will the same gas occupy at atmospheric pressure and 1,800° F.?

8. At what temperature will 1 lb. of air at atmospheric pressure occupy 15 cu. ft.? (Use data of Prob. 1.)

9. A certain gas occupies 10 cu. ft. when at 50° F. and under a pressure of 1 atmosphere. By using two of the fundamental-law formulas, find the volume of the same gas at 80° F. and a pressure of 2.5 atmospheres.

10. Find the pressure exerted by the gas by Prob. 9 when the volume is 8 cu. ft. and the temperature is 100° F. (Use two steps.)

11. What temperature would the gas of Prob. 9 have when its volume is 5 cu. ft. and its pressure is 30 lb. per sq. in. abs.? (Solve in two steps.)

12. Solve Prob. 9 in one step.

13. A quantity of gas at 60° F. and atmospheric pressure has a volume of 7 cu. ft. What pressure will the same gas exert when at 200° F. and in a volume of 6 cu. ft.? (Solve in one step.)

14. At what temperature will the pressure and volume of the gas of Prob. 13 be 30 lb. per sq. in abs. and 5 cu. ft. respectively?

15. A receiver of 15-cu. ft. capacity contains 9 lb. of acetylene. At what temperature will the pressure in the tank become 200 lb. per sq. in. gage?

16. What must be the capacity of a receiver to hold 50 lb. of air at a pressure of 250 lb. per sq. in. gage and at a temperature of 210° F.?

17. When 9 lb. of a certain gas occupy 5 cu. ft., the pressure and temperature are, respectively, 175 lb. per sq. in. gage and 290° F. Which is the value of the gas constant?

18. A tank of 10-cu. ft. capacity contains air at atmospheric pressure and 70° F. Air is forced into this tank until the pressure rises to 200 lb. per sq. in. gage, and the temperature to 75° F. What weight of air has been forced into the tank?

19. If 30.6 lb. of oxygen is confined in a 3-cu. ft. container, what is the density of the gas?

20. If, under certain conditions, the density of air is 0.08 lb. per cu. ft., how much will 88 cu. ft. of the air weigh?

21. What is the density of nitrogen at 100 lb. per sq. in. gage and 80° F.?

22. From the result of Prob. 21 find the density of nitrogen at 80° F. and atmospheric pressure.

23. From the result of Prob. 21 find the density of nitrogen at 1800 lb. per sq. in. gage and 200° F.

24. How many foot-pounds are represented by the shaded area of Fig. 273?

25. A tank held 40 cu. ft. of air at 200 lb. per sq. in. gage. This air is cooled in the tank to 70° F. and its pressure is now 150 lb. per sq. in. gage. How much heat has been extracted and how much vibration work is done on the air?

26. If 6 lb. of air are heated at constant pressure from 60° F. to 150° F., how much heat is added, and how much external and vibration work is done?

27. A compressor delivers 100 cu. ft. of air per min. at a pressure of 100 lb. per sq. in. gage and at 130° F. If this air is cooled, at constant pressure, so that only 90 cu. ft. are delivered at another point, how much heat is abstracted each minute? How much external and vibration work is done during the cooling?

28. It is desired to compress 3 cu. ft. of air at atmospheric pressure to 100 lb. per sq.

in. gage. How much heat must be withdrawn to accomplish this without changing the temperature and where does this heat come from?

29. Compute the work done by 1 lb. of air in expanding from 175 lb. per sq. in. gage to 15 lb. per sq. in gage at a constant temperature of 100° F.

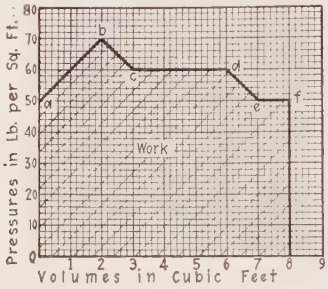


Fig. 273.—Pressure-volume work diagram.

30. During an adiabatic process the temperature of 20 lb. of air changed from 80° to 150° F. How much external work was done on the gas?

31. One pound of air expands adiabatically from 300 lb. per sq. in. abs. and 200° F. to 15 lb. per sq. in. abs. What are its initial volume, final volume, and final temperature?

32. In Prob. 31, how much external work is done by the expanding air and how much vibration work?

33. In an air compressor, 10 cu ft. of air at 100° F. and under a pressure of 14 lb. per sq. in. abs. are compressed adiabatically. The final pressure is 60 lb. per sq. in. abs. Compute the volume and temperature of this air after compression.

34. If, during a polytropic process for which $n = 1.2$, the temperature of 20 lb. of air changed from 80° to 150° F., how much external work was done by the gas? How much heat had to be added?

35. During the compression of an ideal gas 40,000 ft.-lb. of work are expended and 8 B.t.u. are taken from the gas by conduction. How much vibration work is done on the gas?

36. During a compression following the law $PV^{1.3} = a$ constant, the temperature of the air rises from 80° to 200° F. How much heat has been transferred to the cylinder walls per pound of air?

37. If 1 lb. of nitrogen expands polytropically ($n = 1.35$) from 100 lb. per sq. in. gage and 120° F. to atmospheric pressure, what will be the final volume and temperature?

38. Compute the heat added, external work, and vibration work in Prob. 37.

39. If oxygen were expanded adiabatically from an initial condition of 1,800 lb. per sq. in. abs., 2 cu. ft., and 90° F. until its temperature reached −280° F., what would be its final pressure and volume?

DIVISION

MELTING AND FREEZING OF SUBSTANCES

277. Melting Or Fusion is the process by which a substance is changed (Sec. 103) from the solid to the liquid state by added heat.

NOTE.—THE TEMPERATURE AT WHICH A SUBSTANCE MELTS OR FUSES is called its *temperature of fusion*, or simply its *melting point*, see Table 285 for values.

NOTE.—BEFORE PROCEEDING THE READER SHOULD REVIEW carefully the material in Div. 4, starting with Sec. 96, which discusses the three ways in which heat which is added to a substance may be expended, and the three different kinds of work which heat added to or abstracted from a substance may do.

278. Solidifying Or Freezing is the process by which a substance changes (Sec. 161) from the liquid to the solid state; freezing is always accompanied or occasioned by the abstraction of heat from the substance.

NOTE.—THE TEMPERATURE AT WHICH A SUBSTANCE SOLIDIFIES or freezes is called its *temperature of solidification*, or simply its *freezing point*. The usual freezing point (temperature) for any substance is the same as the melting point (Sec. 277) of that substance.

279. All Crystalline Substances Have Definite Temperatures Of Fusion And Solidification.—That is, every substance, as *mercury*, *ice*, *sulphur*, *silver*, in which the molecules are grouped in the form of crystals of a definite uniform structure, has a certain fixed, characteristic temperature, corresponding to a given pressure, at which both melting and solidification occur.

NOTE.—WHEN A CRYSTALLINE SUBSTANCE UNDER A CONSTANT PRESSURE UNDERGOES EITHER MELTING OR SOLIDIFYING, its temperature remains constant from the instant that melting or solidifying begins until the process is completed, as discussed more fully in following Sec. 289.

280. All Non-crystalline Or Amorphous Substances Have Indefinite Temperatures Of Fusion And Solidification.—That is, every substance, as *glass, wax, resin, glue,* in which the molecules are arranged in an indeterminate, irregular and non-uniform formation, have no definitely fixed temperature at which both melting and solidification occur.

Note.—Non-crystalline Substances Assume All Degrees Of Viscosity (Sec. 165) both in melting and in solidifying. If a glass rod is heated in the flame of a blow-torch, it will become soft and may be easily bent. If the heating is continued, the glass will become more and more plastic. Finally, it will begin to melt. But if the heat is still applied, after melting begins, the temperature of the glass will continue to rise. That is, no point is reached, as heat is applied, at which the temperature remains constant for an interval.

281. The Melting And Solidifying Temperatures Of Dissolved Or Alloyed Substances are, generally lower than the melting and solidifying temperatures of the simple substances which compose the solutions or alloys. This principle is of great practical importance in many ways. It provides a ready means (Fig. 274) for producing ice artificially. Also (Fig. 275) it, by virtue of the low melting temperatures of certain alloys, is the basic principle of many fire-extinguishing devices. By varying the proportions (Fig. 276) of the metals used in an alloy, the melting point of the alloy can, within a certain range, be made any desired temperature.

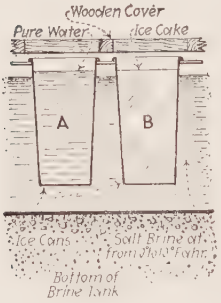


Fig. 274.—Illustrating use of salt brine in artificial ice-making. The salt brine can be cooled far below 32° F.—the freezing point of water—before it begins to freeze.

Example.—When salt is dissolved in water (Fig. 274) the freezing temperature of the brine thus formed may be many degrees lower than the freezing temperature of pure water. Hence, the pure water in the can *A* (Fig. 274) will be frozen into a solid cake of ice, as *B*, when the can is immersed in the low-temperature brine for a sufficient length of time.

Example.—A certain alloy, called *Darcet's Metal,* is composed of 2 parts bismuth, 1 part lead and 1 part tin. The melting temperature of this alloy is 203° F., which is (Table 285) many degrees lower than the melting temperature of either of the component metals.

Example.—An alloy of tin, lead, and bismuth has been used (Fig. 277) for making the fusible elements of safety plugs for steam boilers. The

alloy in the cap, *F* (Fig. 277), absorbs heat from the furnace gases. But normally the conduction of this heat to the water in the boiler proceeds at a sufficiently rapid rate to prevent the temperature of the alloy from reaching the melting point.

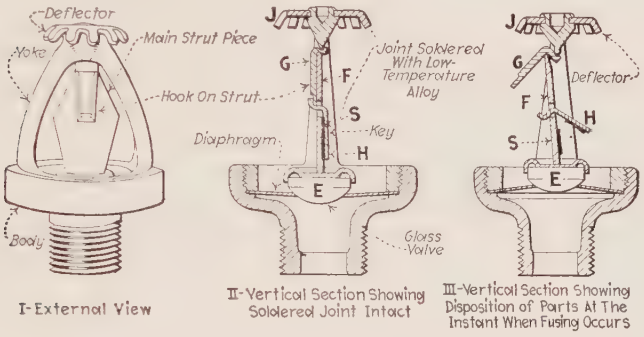


FIG. 275.—Details of *Grinnel* sprinkler head for use in fire-protection systems.

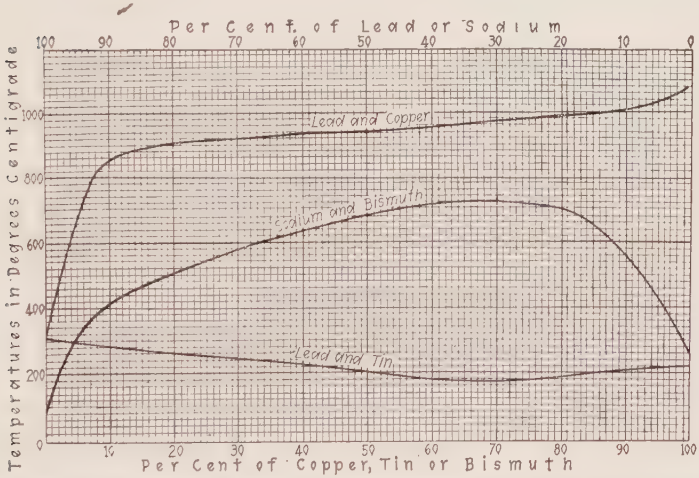


FIG. 276.—Curves showing variations of melting temperatures of alloys corresponding to variations in the proportions of the metal constituents of the alloys.

However, if the water level falls low enough to expose the cap *F* directly to the steam in the boiler, then, the steam not being able to conduct away the heat as rapidly as the heat is absorbed by the cap, the temperature of *F* quickly rises to the melting point of the alloy. Then the cap *F* melts and is blown out. The blowing out of the plug liberates the steam in the boiler and prevents a possible explosion.

282. The Use Of Metal Alloys In The Liberating Devices Of Sprinkler Or Fire Protection Systems (Fig. 275) permits the sprinklers to be adjusted for operation (Fig. 278) at exactly the highest temperature that can be allowed, with safety, in the building which the apparatus is designed to protect.

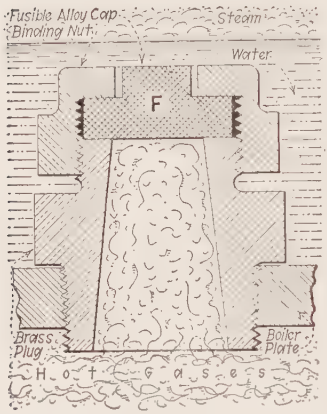


FIG. 277.—Fusible safety-plug for steam boilers.

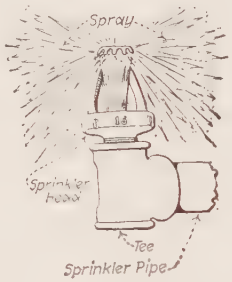


FIG. 278.—*Grinnel* sprinkler-head in action.

EXPLANATION.—The key, *H* (Fig. 275), is soldered to the main strut-piece, *F*, by an alloy, *S*, which fuses at the desired temperature. If the normal temperature of the room in which the sprinkler is installed is 100° F. or less, the fusing temperature of the solder, *S*, is usually fixed at 155° F. If the normal room-temperature is to be between 100° and 150° F., then an alloy with a fusing temperature of 212° F. may be used. Should the air in the room become heated to the fusing temperature of the alloy, the soldered joint, *S*, will be melted out. The key, *H*, and hook, *G*, will thus become disjointed. The glass valve, *E*, being released from the restraint of the strut-piece, *F*, will then be blown out by the pressure of the water beneath. The issuing water (Fig. 278) will be broken into spray by the deflector, *J*, and will, presumably, extinguish the fire.

283. The Utility Of Fusion Pyrometers For Measuring High Temperatures (Fig. 279) depends upon the facility with which the melting temperatures of alloys or compositions of substances can be adjusted to desired degrees of heat intensity. Such pyrometers are commonly used for determining the temperatures of pottery furnaces. They consist of a graduated series of two or more clay pyramids, or *Seger cones*. The pyramids are about 2.5 in. high. They are composed of several different varieties of clay, which are mixed in such

proportions as to give a different melting point to each pyramid in the series. The difference between consecutive melting points is about 35° F. A range of temperature from about 600° to 3,400° F. may thus be covered. The cones are

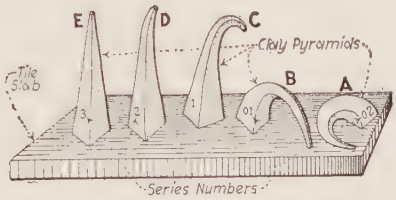


Fig. 279.—A fusion pyrometer—melting temperatures in degrees Fahrenheit are as follows: A = 2,000. B = 2,035. C = 2,070. D = 2,105. E = 2,140.

stamped with numbers. A definite melting temperature corresponds to each number in the series.

Explanation.—When a series of Seger cones, or clay pyramids, is placed in a furnace which is being fired up for service, the cone or pyramid which has the lowest melting point will be the first to lose its upright form. The temperature corresponding to the series-number on a cone or pyramid is reached when the tip of the cone or pyramid has bent over *B* (Fig. 279) so that it just touches the tile surface on which the cone or pyramid stands.

Note.—Fusion Pyrometers Give Only Approximate Temperature Measurements—but these are sufficiently accurate for the purposes for which the cones are properly employed.

284. Temperature Pendants (Fig. 280), for giving approximate indications of flue-gas temperatures in boiler plants, are made by adjusting the proportions of the alloy of which the pendants are cast to give a graded series of melting points. The utility of these devices as they are ordinarily furnished is limited to a range of temperature between 425° and 550° F. There is a 75° difference between the fusing points of the three pendants. They are usually applied by suspending the three pendants in the path of the gases.

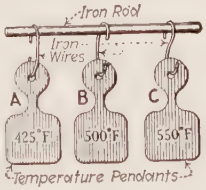


Fig. 280.—Green's temperature pendants—melting temperature stamped on each pendant.

Example.—Suppose the pendants *A*, *B*, *C* (Fig. 280) to be suspended in a boiler breeching. If pendant *A* melts while the others remain intact, then the temperature lies between 425 and 500° F. If pendants *A* and *B* both melt while

pendant C remains intact, then the temperature lies between 500 and 550° F.

285. Table Showing The Melting And Freezing Points (Temperatures) Of Various Substances under atmospheric pressure. Values are from the following authorities: S = SMITHSONIAN TABLES. M = MARKS' MECHANICAL ENGINEERS' HANDBOOK.

Substance	Melting and freezing point, deg. Fahr.	Authority	Substance	Melting and freezing point, deg. Fahr.	Authority
Alcohol	−143	S	Lead	621	S
Aluminum	1,218	S	Magnesium	1,204	S
Antimony	1,166	S	Magnesium chloride	1,306	S
Barium	1,562	S	Magnesium sulphate	302	S
Bismuth	520	S	Mercury	−38	S
Borax	1,366	S	Nickel	2,646	S
Calcium	1,490	S	Oxygen	−360	S
Calcium chloride	1,404	S	Platinum	3,191	S
Carbon[1]—above	6,300	S	Silver	1,761	S
Carbon dioxide[1]	−70.6	S	Sodium	208	S
				224	
Carbon disulphide	−166	S	Sulphur[2]	235	S
				247	
Copper	1,981	S	Tantalum	5,252	S
Glycerine	4	M	Tin	449	S
Gold	1,945	S	Tungsten	6,152	S
Hydrogen	−434	S	Turpentine	14	M
Iodine	236	S	Ice (water)	32	
Iron (pure)	2,786	S	Zinc	787	S

[1] Sublimes (Sec. 163).

[2] Sulphur occurs in three solid forms having the values as shown.

286. Many Substances May Be Changed From The Solid To The Liquid State By Solution.—That is, by mixing them with other substances which are already in the liquid state, as when salt or sugar is dissolved (Sec. 170) in water, or when shellac is dissolved in alcohol. In the dissolution of a solid substance by this process, energy is expended in causing the molecules of the *solute*, or solid substance, to separate from one another and intermingle intimately with the molecules of the *solvent*, or liquid substance. When some solutes are dissolved, even their molecules (or some of them) are broken up into *ions*.

287. The Heat In The Substances, Or In Surrounding Substances, Supplies This Energy.—A portion of the vibration or sensible heat (Sec. 54) of the mixture is (by doing disgregation work) transformed into potential energy due to the mutual rearrangement of the molecules. Therefore, in all mechanical solutions—that is, solutions which occur without violent chemical reactions between the solute and the solvent—heat energy must be absorbed while the process of dissolution is proceeding. The production of *freezing mixtures* depends upon this principle. Such mixtures may be made by mixing certain solid substances, as sodium chloride (common salt) or calcium chloride, with snow or broken ice.

Explanation.—If a quantity of snow or broken ice is placed in a vessel (Fig. 281) and is mixed therein with common salt, the snow or ice will melt quickly. The disgregation heat which the snow or ice must absorb (Sec. 98), in order that melting may occur, is given up by the surrounding objects. If more salt is present than can go into a

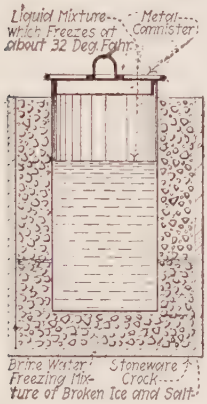


Fig. 281.—Illustrating application of freezing mixture.

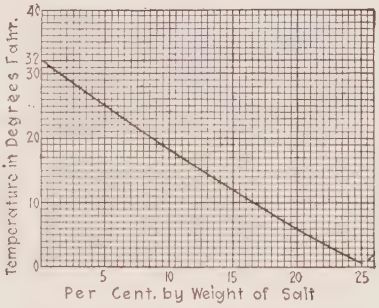


Fig. 282.—The freezing temperature of brine varies with the percentage of dissolved salt.

saturated solution of salt and water, the temperature of the salt-ice mixture will tend to become that at which a saturated solution of salt freezes (−6° F.). The temperature will attain this value if heat does not reach the ice water faster than the ice can melt. If less salt is present than that which is necessary to produce the saturated solution, the temperature of the brine-ice mixture will be higher than −6° F. In all cases, the temperature (Fig. 282) will depend mainly upon the quantity of the dissolved salt. The greater the proportion of salt to water in the brine, the lower the melting temperature of the ice in the brine. If a vessel (Fig. 281) containing a liquid that freezes at about the freezing point of water be submerged in the freezing mixture, the

liquid will be quickly frozen. This is the operating principle of the ordinary household *ice-cream freezer*.

Note.—A Freezing Mixture is one which may be used to produce low temperatures. A mixture containing about 3 parts of snow and 1 part of common salt will produce a temperature of from 4° to 6° below 0° F. A mixture containing 3 parts of calcium chloride and 2 parts of snow will produce a temperature of 50° below 0° F. The mixing of equal parts of nitrate of ammonia and water may result in reducing the temperature of the mixture through 46° F.

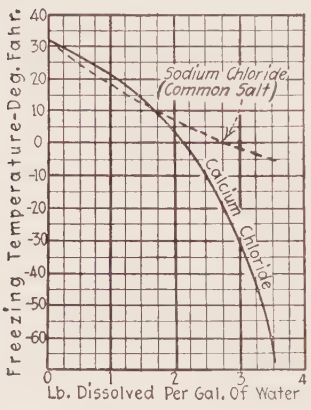


Fig. 283.—Graphs showing freezing temperatures of calcium-chloride and sodium-chloride (common salt) solutions, in water, of different concentrations.

Note.—Water For Extinguishing Fires may, when kept in barrels which are exposed to freezing weather temperatures, be kept fluid by dissolving (see Fig. 283) a quantity of calcium chloride therein. Calcium chloride is preferable, for this purpose, to common salt. The corrosive action of common salt on metals is considerable. Also, the salt tends to creep from the solution, by capillary action, and crystallize on the outside of the containing vessel. If calcium chloride is not obtainable, common salt may be used.

288. The Effect Of Pressure Upon The Melting And Freezing Temperature Of Substances will now be considered. If a body of water has imposed on it a pressure many times greater than the pressure of the atmosphere, it will continue in the liquid state even though its temperature be reduced somewhat below its freezing point (Sec. 278) under atmospheric pressure. But if a mass of lead is melted under atmospheric pressure and is then subjected to a pressure greatly in excess of atmospheric, it will again become solid at a higher temperature than the temperature under which it was melted. These phenomena suggest the following principles: (1) *The temperatures of melting and solidification of any substance which expands while solidifying and contacts while melting is lowered by applying pressure.* (2) *The temperature of melting and solidification of any substance which contracts while solidifying and expands while melting is raised by applying pressure.*

Example.—A small wire (Fig. 284) with weighted ends, *WW*, is slung over a rectangular block of ice. The temperature of the surrounding air remains constantly at 32° F. The pressure, due to the suspended weights, *WW*, which the wire exerts, upon the narrow area upon which it rests, reduces the freezing temperature of that area slightly below 32° F. Hence, the ice under and in immediate contact with the wire begins to melt. Presently, the wire will have cut into the ice-block to a considerable depth. But as the wire descends it will displace the water which results from the melting. The water will gather above the wire. Being relieved from the pressure of the wire, the water will again freeze to ice. The fissure which the wire forms as it descends is thus being constantly closed above the wire. Hence the wire becomes embedded in the ice-block as it cuts its way through. The process of melting under pressure and freezing again when the pressure is relieved is called *Regelation.*

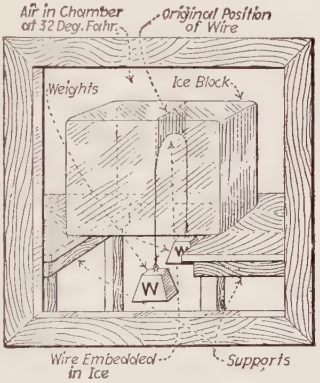


Fig. 284.—Regelation—illustrating effect of pressure on the melting temperature of ice.

Note.—The Freezing Temperature Of A Body Of Water May Be Lowered from 32° to about 31.9865° F. by adding 14.7 lb. per sq. in. (1 atmosphere) to the normal atmospheric pressure on its surface, and the freezing temperature will decrease approximately 0.013,5° F. for each additional atmosphere of pressure added.

289. Latent Heat Of Melting Or Fusion will now be considered. As defined and explained in Sec. 106: "Latent heat is the heat energy which is required to produce changes in the physical state (Sec. 49) of a substance." It has been found by thousands of experiments that, for each substance, a certain definite amount of heat is required to convert, into the liquid state, 1 lb. of the solid substance which is already at its melting temperature. Following Table 291 shows values. This amount of heat which is required to convert 1 lb. of a substance, which is in the solid state and at its melting temperature into the liquid state, at the same temperature, is called the latent heat of melting for the substance. See also Sec. 103.

Explanation.—If a quantity of cracked ice (Fig. 285) be melted over the flame of a spirit lamp, the mercury in the Fahrenheit thermometer

will stand at the 32° mark until the ice is entirely changed to water. But the instant the last vestage of the original mass of ice has disappeared, the mercury will begin to rise. Although the thermometer indicates no rise of temperature while the melting is in progress, the ice is, nevertheless, constantly absorbing heat from the flame. But this heat is wholly expended as disgregation work—in overcoming the cohesion among the molecules of the ice crystals (Sec. 50) and in separating them. That is, the energy of this latent or unindicated heat is used up in the work of disintegrating the compact molecular structure that exists in ice and in giving the molecules that freedom under which they exist in water.

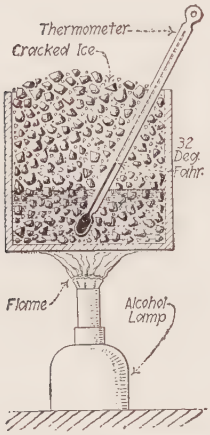


Fig. 285.—Illustrating latent heat.

Hence, the "latent" heat which is not revealed by the thermometer resides within the water in the form of molecular potential energy, or as the additional energy of position which the molecules possess by virtue of their increased distance from one another. This phenomenon is, presumably, present in the melting of all substances.

290. Similarly, When A Substance Changes From The Liquid To The Solid State, The Latent Heat Energy Existing Within The Liquid Is Given Up to surrounding substances. Or, stating the same idea in a different way: As a substance is changed from the liquid to the solid state, the latent heat energy (disgregation heat) which resides within the liquid must, to effect the change, be abstracted from the liquid. Hence (Fig. 286) the temperature of any substance which has a determinate freezing point (Sec. 278) continues constant while the substance is changing from the liquid to the solid state.

Example.—A crucible containing molten zinc (Fig. 286) at a temperature of 896° F. is permitted to cool. The liquid zinc begins giving up its sensible, or vibration heat (Sec. 97). Therefore, the temperature falls gradually, *AB*, until 787° F., which (Table 285) is the temperature of solidification, is reached. The temperature remains at 787° (*BC*, Fig. 286) until the zinc has completely solidified. During this *BC* interval the zinc is giving up its latent heat of melting, or disgregation heat. When all of this heat has been abstracted, the solid zinc then again begins giving up its sensible or vibration heat. Hence, the gradual fall of temperature is resumed as shown at *CD*.

Note.—It Is Probably True That The Melting Of Every Crystalline Substance Requires The Expenditure Of A Certain Quantity Of Heat, depending upon the nature of the substance, to change the molecular arrangement which exists in the solid state of the substance to that which exists in the liquid state. This, however, cannot be asserted without qualification, since the melting temperatures of some substances are so extremely high that accurate observations of the phenomena involved cannot be made.

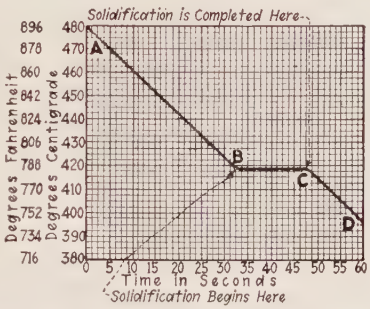


Fig. 286.—Graph showing temperature conditions during the cooling and solidification of a mass of molten zinc.

Note.—The Early Investigators Of Heat Phenomena Gave The Name Latent Heat to the heat energy (disgregation heat) which is expanded in reconstructing the molecular arrangements of melting substances. It was presumed that this energy simply soaked into a melting substance and remained concealed therein in a deadened or dormant condition.

Note.—Dr. Black, A Scotch Physicist, In 1760 Determined The Latent Heat Of Ice.—He placed two vessels, one containing 1 lb. of ice, and the other containing 1 lb. of water at 32° F., in a chamber in which the temperature was kept constant at about 47.3° F. The temperature of the 1 lb. of water rose to 39.2° in 0.5 hr. The melting of the 1 lb. of ice and the heating of the resulting water to 39.2° consumed 10.5 hr.

The experimenter assumed that during each ½ hr. equal quantities of heat passed from the surrounding air into the 1 lb. of ice and the 1 lb. of water. That is, (so Black computed) the ice received $39.2 - 32 = 7.2$ *B.t.u. per* 0.5 *hr.* Hence, in 10.5 hr. the ice absorbed $(10.5 \div 0.5) \times 7.2 = 151.2$ *B.t.u.* Only 7.2 B.t.u. were required to raise the temperature of the melted ice to the temperature of the chamber. Therefore, a *quantity of heat* $= 151.2 - 7.2 = 144$ *B.t.u.*—the latent heat of ice—was presumed by Dr. Black to have been absorbed and stored in the water in a "latent" or dormant condition.

Dr. Black's method was not strictly accurate because, actually, heat transfer is, as explained in Div. 5 dependent not only on the time during which the heat flows but also on the average difference between the temperature of the cold body and that of the hot body—the thermal pressure. Now, the average thermal pressure forcing heat into the 1 lb. of water was, actually, slightly different from that which forced heat into the 1 lb. of ice. Hence, Dr. Black's result was inaccurate, because he assumed that both of these thermal pressures were the same. A more accurate method of determining the latent heat of melting is the method

of mixtures (similar to that of Sec. 94). It is remarkable how nearly correct Dr. Black's result actually was.

Later and more consistent determinations have shown that the latent heat of melting of ice is more accurately 143 3 B.t.u. per lb. However, the value of 144 B.t.u. per lb. is the one which is commonly used in engineering work.

291. Table Showing Latent Heats Of Melting Or Fusion Of Different Substances.—The values shown here have been computed from the SMITHSONIAN TABLES.

Substance	Latent heat of melting, in B.t.u. per pound
Aluminum	138.2
Bismuth	22 75
Copper	75 6
Iron, gray cast	41.4
Iron, white cast	59.4
Iron slag	90.0
Iodine	21.08
Ice	143.33
Lead	9.65
Mercury	5.08
Nickel	8.35
Platinum	49 0
Silver	37.9
Sulphur	16.87
Tin	25 2
Zinc	50.63

NOTE.—STRICTLY, THE LATENT HEAT OF MELTING OF A SUBSTANCE WILL VARY WITH THE PRESSURE WHICH IS IMPOSED ON THE SUBSTANCE WHILE IT IS MELTING, if the substance expands or contracts due to the melting. This is because that if the substance changes volume in melting external-work heat will (unless the melting occurs in a vacuum) have to be supplied—in addition to the disgregation heat—to do the external work which is occasioned by any change of volume. However, as explained in Sec 103, the amount of this external work is so small in practical cases that it may be safely neglected.

292. The Heat Required For Melting A Given Weight Of A Substance together with that required to warm the substance to its melting point, may be computed by the following formula:

$$Q = W[C(T_M - T) + L_M] \quad \text{(B.t.u.)} \tag{240}$$

Wherein: Q = heat, in British thermal units, required for warming and melting the substance. W = weight of substance, in pounds. T_M = temperature, in degrees Fahrenheit, at which the substance melts. T = initial temperature, in degrees Fahrenheit. C = mean specific heat of the substance, between T and T_M, see Table 90. L_M = latent heat of melting, in British thermal units per pound, see Table 291.

EXAMPLE.—A block of ice weighs 201.5 lb. Its temperature is 29° F. How much heat will be required to melt it? SOLUTION.—By Table (90), the *specific heat of ice* = 0.504 *B.t.u. per lb.* By Table (291) the *latent heat of melting of ice* = 143.33 *B.t.u. per lb.* Hence, by For. (240), the *required heat* = $Q = W[C(T_M - T) + L_M] = 201.5 \times \{[0.504 \times (32 - 29)] + 143.33\} = 29{,}186$ *B.t.u.*

EXAMPLE.—A copper ingot weighs 55 lb. Its temperature is 80° F. How much heat will be required to melt it? SOLUTION.—By Table (90) the *specific heat of copper* = 0.093 *B.t.u. per lb.* By Tables 291 and 285, the latent heat of melting and the melting temperature of copper are, respectively, 75.6 *B.t.u. per lb.* and 1981° F. Hence, *the required heat* = $\{[(1981 - 80) \times 0.093] + 75.6\} \times 55 = 13{,}882$ *B.t.u.*

QUESTIONS ON DIVISION 9

1. What chiefly distinguishes the molecular structure of a substance in the solid state from the molecular structure of the same substance in the liquid state?
2. What is meant by *temperature of fusion*? *Temperature of solidification*?
3. What characteristic of substances apparently determines whether the melting temperature of a substance shall be constant or variable?
4. The freezing temperature of a mixture of sugar and water is lower than the freezing point of pure water. Why is this?
5. What are *freezing mixtures*? How may they be utilized practically?
6. What, in general, is the effect in the melting points of two or more different metals when an alloy is formed with the metals? In what respect is this principle of practical utility? Give an example.
7. In what manner, other than by melting, can some solid substances be reduced to a liquid state?
8. What is a *solute*? A *solvent*?
9. In what ways do variations of pressure affect the melting and freezing temperatures of substances?
10. What is meant by *latent heat of fusion*?
11. What becomes of the latent heat in a liquid substance while the substance is solidifying?
12. Describe and give values for Dr. Black's latent-heat experiment.

13. Does the latent heat of fusion perform a constant action function in a liquid substance, that is does it do work—or does it exist in a state of dormancy? In any event, what is the function of latent heat of fusion?

14. Why did the early experimenters use the term "latent" in defining the non-sensible heat that goes into melting substances?

15. What is a *fusion pyrometer?*

16. Explain the use of Seger cones.

17. What are *temperature pendants?*

PROBLEMS ON DIVISION 9

1. How much heat is required to change 300 lb. of ice at 22° F. to water at 32° F.?

2. An ice-can (Fig. 274) contains 258.3 lb. of water at 65° F. How much heat will pass from the water in the can to the brine in the tank while the water is freezing to a solid block of ice at 32° F.?

3. What is the approximate freezing temperature of a mass of pure water if the gage pressure on its surface is 110 lb. per sq. in.?

4. A ton of tin at a temperature of 80° F. is heated and melted in a crucible to 660° F. How much heat is absorbed by the tin?

DIVISION 10

VAPORIZATION

293. Vaporization is the change in state (Sec. 49) of a substance which occurs when the substance is transformed from the liquid state into the vapor form of the gaseous state. See Sec. 225 for the distinction between a vapor and a gas. Vaporization is a common phenomena and one of great practical importance.

EXAMPLES.—In the steam power plant (Div. 15) it is vaporization that changes the boiler water into steam when the water is heated. In the refrigerating plant (Div. 18) it is the vaporization of the liquefied ammonia or other liquefied gas which indirectly produces the artificial ice and the low temperatures which are necessary in cold-storage houses. It is due almost wholly to vaporization that cooling towers and spray ponds (see the author's STEAM POWER PLANT AUXILLIARIES AND ACCESSORIES) cool the circulating water. In the home, it is vaporization which drys the family "wash."

NOTE.—STEAM IS MERELY WATER VAPOR or, as it is sometimes called, *aqueous vapor*. Hence, as will be explained in Div. 11, much valuable information concerning the properties of water vapor may be obtained from steam tables, an example of which is given in Table 394.

294. There Are Two Kinds Of Vaporization: (1) Evaporation. (2) Ebullition. *Evaporation* (Fig. 155-*I*) *is vaporization which occurs only at the free surface of a liquid.* Evaporation takes place only below the boiling point of a liquid. *Ebullition* (Fig. 155-*II*) *or boiling is vaporization which takes place from within the body of a liquid,* the evolved vapor passing through the liquid to the surface. Each of these two forms of vaporization is discussed in succeeding sections.

NOTE.—SUBLIMINATION (Fig. 155-*III*) is sometimes considered as a form of evaporation. But in this book it is deemed best to treat it as a distinct phenomenon. It is discussed in Sec. 163.

295. Evaporation is occurring about us continually. Water—or any liquid—left in an open vessel gradually disappears. But some liquids evaporate more rapidly than others. Thus,

alcohol evaporates more rapidly than water; ether evaporates more rapidly than alcohol. In each of these cases the liquid which evaporates is transformed into a vapor and passes away as such.

Note.—A "Volatile" Substance is one which will evaporate freely at a relatively low temperature. The term "volatile," however, is generally used only in comparing two or more substances. One substance is said to be more volatile than a second if, at a given temperature, the first substance tends to evaporate more freely than the second. Thus, alcohol is more volatile than water and less volatile than ether. Of two substances, the more volatile will, for a given pressure, have the lower boiling point (Sec. 315) and will, for a given temperature, have the greater vapor pressure (Sec. 304).

296. Evaporation Of Liquids Occurs At All Temperatures provided the space which is in contact with the liquid does not contain a saturated (Sec. 305) vapor of the liquid. Many examples of this fact are matters of common observation.

Example.—The moisture from wet clothes which have been "hung out to dry" evaporates more rapidly in hot dry weather.

Explanation.—The Theory Of Evaporation is this: The molecules of all substances which are at temperatures above 0 deg. absolute, that is which contain heat energy, are (Sec. 45) in continuous motion. In the case of a liquid, the motion of the molecules is rapid and occurs throughout the entire body of the liquid mass. Now, while these rapid molecular movements are occurring, certain liquid molecules collide continually with others which are similarly vibrating about rapidly. Due to the impact of these collisions, some molecules attain velocities much greater than the average velocity of the molecules in the mass. If the molecules which thus have acquired velocities greater than the normal happen to be near the surface of the liquid, then they may be projected (Fig. 287) out into the space above the liquid. Thus they become gas or vapor molecules. In the aggregate they form a vapor in the space above the liquid. During the process of evaporation into air, the space above the liquid is occupied by a mixture of air molecules and vapor molecules. The vapor molecules occupy portions of the large (relatively) spaces between the air molecules.

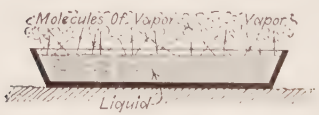


Fig. 287.—Illustrating evaporation or surface-vaporization.

297. When The Liquid Is Unconfined The Flying Off Of The High-velocity Molecules Continues until, ultimately,

all of the liquid molecules disappear. Then complete vaporization has occurred. The liquid has "evaporated."

Note.—When Heat Is Added To The Liquid—when it is warmed—the velocity of its molecules is increased and its evaporation is thereby hastened.

298. The Laws Of Evaporation are: (1) *It increases with the temperature.* (2) *It increases with the extent of surface exposed by the liquid.* (3) *It is much greater into dry air than into air which contains vapor. That is, it decreases as the saturation increases* (Sec. 305). (4) *It increases with the rate of removal of the vapor from the surface of the liquid* as some vapor molecules near the liquid surface tend to return to the liquid body if the vapor is not removed. (5) *The rate of evaporation is increased by diminishing the pressure on the exposed liquid surface* and vice versa. (6) *The rate of evaporation depends on the nature and concentration of any substances which may be dissolved* (Sec. 286) *in the liquid.* Formulas for computing the actual rate of evaporation of water under various conditions are given in the author's Steam Power Plant Auxiliaries and Accessories.

299. Evaporation Increases With The Temperature Of The Liquid.—This follows since (Sec. 55) an increase in the temperature of the liquid is equivalent to an increase in the average velocity of molecular motion of the liquid molecules. When the temperature of a liquid is increased, the number of liquid molecules, which in a given time attain the high velocity which is necessary to project them into the space above the liquid, is increased correspondingly. Thereby the evaporation is increased.

Examples.—Wet objects dry more rapidly when placed on a radiator or near a hot stove. Damp objects are dried quickly by passing a hot iron over them; a cold iron has no effect. A sprinkled street pavement on which the sun is shining will dry promptly while one in the shade will remain wet.

300. Temperatures May Be Decreased By Evaporation (Fig. 288). When a certain weight of a liquid is vaporized, by evaporation or otherwise, then an amount of heat equal to the *latent heat of vaporization* of that weight of the liquid is abstracted from the liquid and air and objects which are adja-

cent to it (latent heat of vaporization is discussed in following Sec. 322). Thereby the remaining liquid and adjacent bodies are cooled. There are many practical examples of this phenomenon. A few are given below.

Explanation.—Evaporation is in reality an escape, from the surface of the liquid, of those liquid molecules which have acquired the highest velocities—which represent the greatest heat energy per molecule.

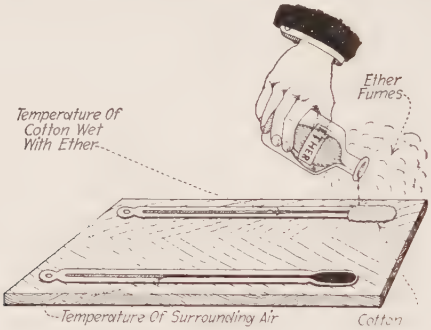


Fig. 288.—Illustrating the cooling effect of evaporation.

Hence, the continual projection of these molecules from the liquid results in a correspondingly continual decrease in the average velocity—temperature—of the molecules which remain. The temperature of the remaining liquid will therefore decrease until no more heat is lost from it by evaporation than it receives from surrounding objects.

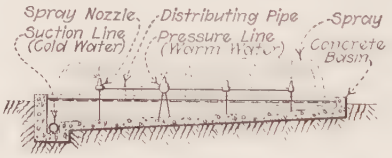


Fig. 289.—Spray cooling pond. The evaporation from the sprays and from the surface of the pond cools the water.

Examples.—A small quantity of ether dropped on the back of the hand will evaporate very quickly: Coincidentally, an intense cooling sensation will be felt where the ether touches the hand. If the ether is dropped on cotton (Fig. 288) which is wrapped around a thermometer bulb, the thermometer will indicate an immediate and pronounced temperature decrease. The temperature of condenser circulating water, which is used over and over again, is reduced by evaporating a small portion of it in a *cooling pond* (Fig. 289), *a cooling tower* (Fig. 290) or with spray nozzles (Fig. 291). Drinking water is kept cool in hot dry locali-

ties by placing it in a porous earthenware jar (Fig. 292) which is hung in a shady windy place; the water which seeps through to the surface of the porous jar is evaporated and thereby the remaining water in the jar is maintained cool. The evaporation from a specially constructed porous earthenware vessel (Fig. 293), which has been submerged in and satur-

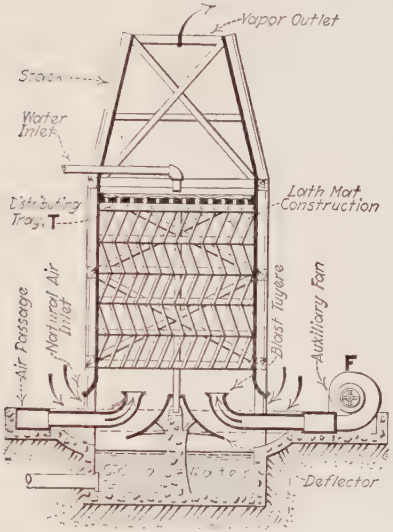


Fig. 290.

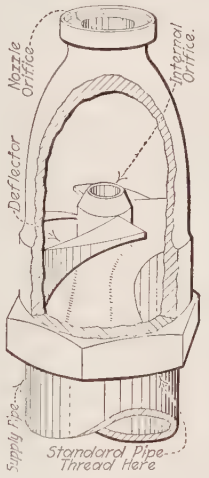


Fig. 291.

Fig. 290.—Cooling tower. (Warm water enters the distributing tray, *T*, and falls in fine streams over the lath checker-work. A current of air from the fan, *F*, along with some air drawn in by natural draft cools the falling water by evaporation.)

Fig. 291.—Spray nozzle with part of side cut away. (The nozzles break the water into fine droplets, thus exposing a large surface for contact with the air thereby causing rapid evaporation.)

ated with, water, maintains at a relatively low temperature the food contained therein. Solid carbon dioxide may be made by the cooling effect of liquid carbon dioxide evaporating in a bag (Fig. 294).

Example.—Freezing Water By The Evaporation Of Ether may be effected with the apparatus shown in Fig. 295. The beaker is placed on a thin film of water on the wooden block. The block serves as a heat insulator. By blowing air through the ether with the bellows, the ether is evaporated rapidly. It absorbs the heat required for its evaporation from adjacent objects. Thereby the water film is transformed to ice: The beaker is "frozen" to the block with a layer of ice. In refrigeration plants, the evaporation of the liquid ammonia in the cooling coils (Fig. 296) abstracts (indirectly, see Div. 18 on Refrigeration) heat from the water in the freezing cans. Thus the water in the cans is changed into ice.

Fig. 292.—Porous earthen water jar or "olla" used for cooling water in hot dry climates. (Courtesy Santa Fe Railroad.)

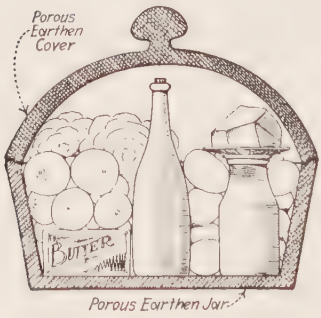


Fig. 293.

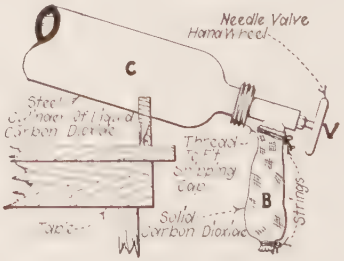


Fig. 294.

Fig. 293.—Porous earthen cooling vessel. Food articles are placed inside. Entire vessel is then submerged in water for about 3 min. Water soaks into porous walls. Subsequent evaporation of water from outside of walls produces cooling effect.

Fig. 294.—Method of making solid carbon dioxide. (Opening *V* permits liquid carbon dioxide to flow into cloth bag *B*. Its rapid vaporization therein, due to the reduced pressure, causes the formation of carbon-dioxide snow in *B*.)

301. Condensation is the opposite of vaporization. It is the process by which a substance changes from the gaseous to the liquid or solid state. As explained hereinafter, conden-

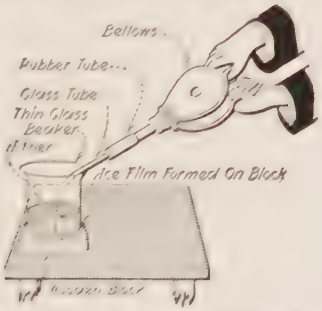


FIG. 295.—Water frozen by the rapid evaporation of ether.

sation of a vapor may be due to either an abstraction of heat (cooling) when the pressure remains constant or to compressing the vapor when the temperature remains constant. Or it may be due to a combination of the two conditions

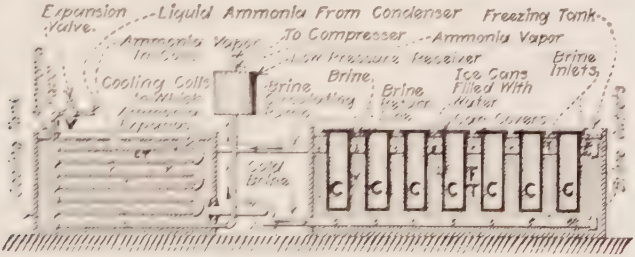


FIG. 296.—Diagram of cooling coils and brine system used in making "can" ice. (Liquid ammonia, when released through *V*, vaporizes and abstracts heat equivalent to its latent heat of vaporization from the brine in *CT*. The brine is then circulated through the freezing tank *FT*. Thereby the water in the cans, *C*, is frozen.)

EXAMPLES.—In the condenser (Fig. 297) in a steam-power plant, the steam is condensed into water by abstracting heat from it with cold water. Economies, as explained in Div. 15 result from the condensing operation. In a compression refrigeration plant (see Div. 18), the compressed ammonia vapor is condensed into liquid ammonia in an ammonia condenser.

302. All Substances Increase In Volume When Vaporized And Decrease In Volume When Condensed.—That is, their volumes increase (Fig. 298) when they are transformed from the liquid to the gaseous state and decrease when they are

transformed from the gaseous to the liquid state. All substances (Table 303) undergo very great changes of volume while vaporizing or liquefying at moderate pressures.

EXAMPLES.—One (1) cu. ft. of water at 212° F., will expand into about 1,604 cu. ft. of steam at atmospheric pressure; see also Fig. 298. Also, 9.47 cu. ft. of carbonic acid gas (carbon dioxide or CO_2), at 32° F., in a manometer gas tank, will contract into 1 cu. ft. of liquid carbonic acid when condensed into a steel drum.

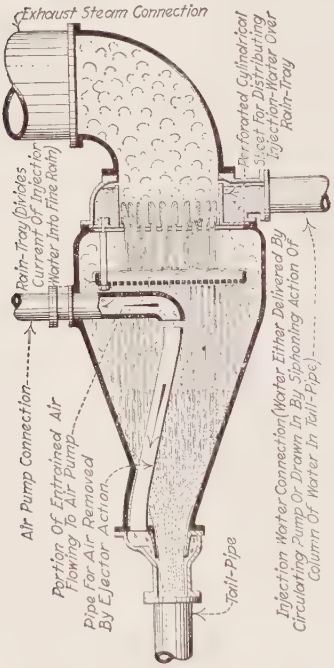

Exhaust Steam Connection
Perforated Cylindrical Steel For Distributing Injection-Water Over Rain-Tray
Rain-Tray (Divides Current Of Injection Water Into Fine Rain)
Air Pump Connection
Portion Of Entrained Air Flowing To Air Pump
Pipe For Air Removed By Ejector Action
Tail-Pipe
Injection Water Connection (Water Either Delivered By Circulating Pump Or Drawn In By Siphoning Action Of Column Of Water In Tail-Pipe)

FIG. 297.

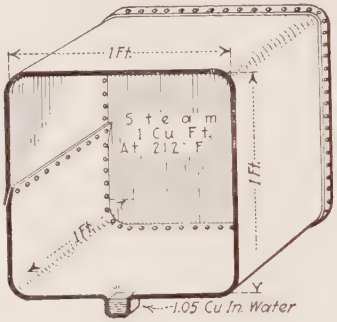


FIG. 298.

FIG. 297.—Sectional view of Wheeler barometric ejector condenser.

FIG. 298.—Showing relative volumes of the same weight of steam and water. (At 212° F. and 14.7 lb. per sq. in. pressure, 0.000,607 cu. ft.—or 1.05 cu. in.—of water will make 1 cu. ft., or 1,728 cu. in. of steam.)

303. Table Showing Specific Volumes Of Various Substances In The Liquid and Gaseous States. (Marks' MECHANICAL ENGINEERS' HANDBOOK.)

Material	Boiling pressure, lb. per sq. in. abs.	Boiling temperature, deg. Fahr	Specific volume = cu ft. per lb.		Ratio = $G \div L$
			L Liquid	G Gas	
Water	14.7	212	0.0167	26.79	1604
Ammonia	14.7	−27.2	0.0237	18.02	760
Carbon dioxide	503.5	32	0.01759	0.1666	9.47
Sulphur dioxide	14.7	13.7	0.01130	5.38	477

304. Vapor Pressure Or Vapor Tension (Fig 299) is the pressure exerted by a body of vapor. It may be conveniently measured in pounds per square inch, inches mercury column, or in any other pressure unit (Sec. 7). The molecules comprising the vapor of a vaporized liquid act (Sec. 50) precisely as do those of a permanent gas. They produce a pressure by bombardment of the walls of any enclosing vessel.

Example.—The most important example of vapor pressure is the pressure exerted by steam (Fig. 299) which is aqueous or water vapor.

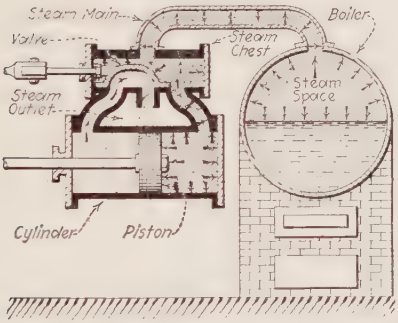


Fig. 299.—Vapor pressure exerted by water vapor (steam) on confining walls.

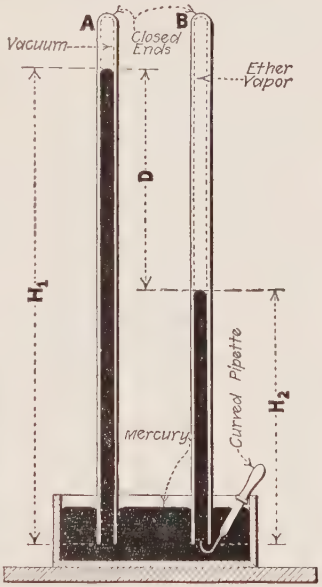


Fig. 300.—Illustrating the principle of vapor pressure.

Example.—Tube *A* in Fig. 300 in reality constitutes a barometer as explained in Sec. 10. The height of mercury column, H_1, is the height which is supported by the atmospheric pressure. If now a drop of ether be introduced into the tube with a curved pipette, as shown at *B*, the mercury column will immediately be forced down to the height H_2. The difference, *D*, in the heights of the two mercury columns will be the vapor pressure, expressed in inches mercury column, which is exerted by the ether vapor. The bombardment of the ether-vapor molecules creates the pressure which forces the mercury column down. The pressure of saturated ether vapor at room temperature may be as great as 16-in. mercury column.

Note.—Vapor Pressure Is Exerted Wherever There Is A Vapor.—While the effects of vapor pressure are most apparent when the vapor is confined in a closed vessel such as a steam boiler or a closed-end tube like that of Fig. 300, an unconfined vapor exerts a pressure, just as does any gas, on the objects in and around it. Thus, water

vapor in the air exerts a part of the observed pressure on the earth's surface—land and water—and on all objects in the locality where the vapor exists.

Example.—Suppose the atmospheric pressure as shown by a barometer is 14.5 lb. per sq. in. and that the air is mixed with saturated water vapor at 80° F. The vapor pressure due to aqueous vapor at 80° F. is (by a steam table) about 0.5 lb. per sq. in. Hence, the pressure due to the oxygen, nitrogen, and other relatively non-condensable constituents of the air is $14.5 - 0.5 = 14.0$ *lb. per sq. in.* That is, a cubic foot of the air will contain only as much of the non-condensable gases as if it were free of water vapor and at a pressure of 14 lb. per sq. in. When the quantity of a gas which is over water is being measured, this effect must be considered.

305. A Saturated Vapor is any vapor which cannot have heat abstracted from it or be compressed at constant temperature without partially condensing. That is, a vapor is saturated when its molecules are so densely packed in the given space that additional molecules arising from the liquid would tend to reduce the molecular arrangement to that which exists in the liquid state of the substance. See also Sec. 354 for another definition of saturated vapor.

Note.—When A Vapor Is Saturated, The Pressure Exerted By The Vapor presses, as it were, down on the liquid and, in effect, prevents further liquid molecules from entering the space where the vapor exists. There is an equilibrium between the pressure exerted by the vapor and the pressure exerted by the liquid. A vapor which is confined in a closed vessel may and will become saturated (Fig. 301-*II*) provided that a portion of the liquid remains in the vessel. But a vapor which is unconfined (Fig. 301-*I*), which is free in the open air, cannot become saturated because the vapor molecules diffuse and seep away through the air (note under Sec. 304) and are wafted away by air currents.

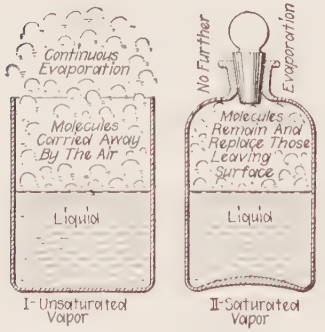


Fig. 301.—Showing how confining vapor prevents further evaporation.

Explanation.—The water in the closed cylinder (Fig. 302) is assumed to be in process of vaporization at a certain temperature, T. Due to the violence of their vibratory motion, the liquid molecules at the surface are (Sec. 296) incessantly darting into the space between the water and the piston. Thus they become vapor molecules. But, while darting

hither and thither in the enclosed space, some of these vapor molecules strike the surface of the water. These molecules thereby resume their original status as water molecules.

For a time, a greater number of molecules will be leaving the water to become vapor molecules than will be returning thereto to again become liquid molecules. The disparity between the number of departing and the number of returning molecules will, however, gradually diminish. Finally, the number of molecules arising from the water as vapor will equal the number returning thereto as liquid.

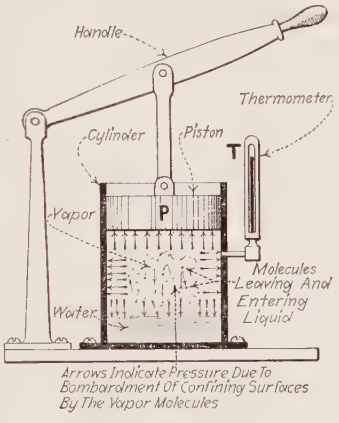


FIG. 302.—Illustrating principle of vapor-saturation.

Hence, if the piston is still maintained in its original position, the total number of vapor molecules in the space between the piston and the water will thenceforth continue constant. When this condition of equilibrium is attained, the vapor is saturated.

NOTE.—THE WORD "SATURATION" IS COMMONLY USED TO INDICATE THE CONDITION OF THE AQUEOUS VAPOR IN THE AIR IN ANY SPACE INTO WHICH WATER HAS VAPORIZED.—In such cases the air is incorrectly said to be saturated with the vapor. (Instead it should be said to be *mixed* with saturated vapor.) This "saturated-with-the-vapor" idea is the popular, though scientifically inaccurate, interpretation of the term. It results from an erroneous theory, which formerly prevailed, that air preserves the vaporized condition of a substance by holding, like a sponge holds water, the vapor molecules suspended in the pores or spaces between its own (the air's) molecules. The following terms are (PSYCHROMETRIC TABLES, W. B. No. 235; *U. S. Department Of Agriculture*) incorrect: "The air is partly saturated with moisture." "Weight of aqueous vapor in a cubic foot of saturated air." The following is correct: "Weight of a cubic foot of saturated aqueous vapor." That is, the air is not "saturated;" it is the vapor which is saturated.

EXAMPLE.—Steam in a boiler which is under pressure, assuming of course that there is water in the boiler in contact with the steam, is a good example of saturated aqueous vapor. In fact, such is called saturated steam.

306. Dalton's Laws For Vapors, discussions of which follow, are: (1) *The pressure of a saturated vapor depends only on its temperature.* (2) *The total pressure of a mixture of gases or vapors which have no chemical action on each other, is equal to*

the sum of the pressures which each would exert seperately if it were alone in the space occupied by the mixture. These laws are stated a little differently by various authorities but the differences are of minor importance—the laws, as stated here, are believed to enumerate the governing facts.

Note.—The Second Of The Above Laws Is Called "Dalton's Law Of Partial Pressures."—The law does not hold for vapors of liquids which dissolve in one another either partially or in all proportions (Gregory and Hadley, Manual Of Mechanics And Heat, p. 237). See discussion of this law as applied to gases in Sec. 276.

Example Of Exception.—Gasoline is a mixture or solution of many liquids having different boiling points (Sec. 315). The vapor pressure of each of these liquids is sufficient so that if the combined vapor pressure were the sum of the individual vapor pressures, a pressure of much more than atmospheric pressure would be developed and the liquid would boil at ordinary temperatures. Similarly it would be impossible to condense the gasoline vapor as it is condensed in its purification by distillation. The combined vapor pressure of the gasoline constituents is more nearly an average than a sum of their individual vapor pressures.

307. The Pressure Of A Saturated Vapor Depends Only On Its Temperature.—If enough ether is introduced into tube *B* of Fig. 300, so that it does not all vaporize at atmospheric temperature, then *D* will measure the pressure, in inches of mercury column, of the *saturated* ether vapor at that temperature. If, then, the saturated vapor in *B* be warmed by passing a bunsen-burner flame across it, more of the ether will be vaporized and the vapor will then exert a greater pressure and force the mercury still further down. Cooling the vapor has the opposite effect. By measuring the pressures exerted by the vapor at different temperatures, it can be shown that the pressure (Sec. 308) of a saturated vapor is determined only by its temperature. The pressure is independent of its volume if the temperature remains as shown above, the vapor determines its own volume for any given temperature.

Example.—By referring to a saturated-steam table (Sec. 394) it will be noted that for each pressure there is a definite temperature and vice versa. A saturated-steam table is merely a saturated-water-vapor table.

Explanation.—For each temperature of a gas or vapor, there is (Sec. 55) a certain speed of vibration of its molecules. Since the vibration speed of the molecules determines the pressure which the gas exerts it follows that the pressure is determined by the temperature. If the

temperature of the vessel which contains the vapor is raised, the molecules are projected more frequently from the liquid. Hence, more vapor molecules must then accumulate above the liquid to insure equilibrium between the vapor and its liquid. Thereby the number of molecules in the vapor space is increased. Furthermore, their velocities are increased by the temperature increase. Hence the pressure exerted by the vapor is increased correspondingly.

308. The Saturation Pressure Of A Vapor is defined as the pressure which, at a given temperature, the vapor exerts when completely saturated. The saturation pressure is the maximum pressure which a vapor can exert at any given temperature. Saturated-steam tables (Sec. 394) give the saturation pressure for water vapor or steam.

309. Condensation Occurs When Heat Is Abstracted From A Saturated Vapor Or When Vapor Is Compressed Without Changing Its Temperature.—Examination of any saturated-vapor table (Div. 11) will disclose that the density (weight of a cubic foot) of saturated vapor increases with its temperature. Now, if heat is abstracted from a saturated vapor, the vapor will be cooled and will contract—as all substances do when their temperature is decreased. Or, if the saturated vapor is compressed, its temperature remaining constant, it will then also occupy a smaller volume. Hence, abstracting heat from or compressing a saturated vapor causes a given weight of the vapor to occupy less volume—that is, increases the density of the vapor. But, by the vapor tables, the density of the vapor cannot have a value greater than given in the table for the given temperature. Therefore, a portion of the vapor must condense and occupy only that smaller volume which it requires when in the liquid state. If the vapor has been compressed without changing its temperature, then the resulting mixture of liquid and vapor will still exert the same vapor pressure as before compressing the vapor; but the vapor will now occupy a smaller volume than before. If the vapor has suffered an abstraction of heat, it may exert a smaller pressure and exist at a lower temperature than before heat was abstracted from it.

Note.—Heat Is Abstracted From Water Vapor In A Steam Condenser.—Steam may, after being used by an engine or turbine, be admitted to the condenser which is maintained at a low tempera-

ture by circulating cold water through it. The exhaust steam is thus cooled to a relatively low temperature at which it can exert only a small pressure and has a smaller density. The greater portion of the exhaust steam from the engine or turbine is thereby condensed—only a small weight of the original vapor remaining as vapor in the condenser. How economies may result through the operation of a condenser in connection with an engine or turbine is explained in Sec. 513.

Explanation.—Imagine a closed vessel which contains a liquid and its vapor at a certain temperature. The vapor is saturated because it is in contact with the liquid and molecules are passing from the liquid into the vapor at the same rate as molecules are passing from the vapor into the liquid (as explained under Sec. 305). If, now, the vessel is cooled from without, the liquid will first be cooled (because it is a better conductor of heat than the vapor). Thus, the average velocity of the liquid molecules will be decreased. Less of the liquid molecules will then have that abnormal velocity which is necessary to project them into the space above the liquid level. But, for the instant at least, the vapor molecules still possess the same velocities as before heat was abstracted. Hence, the equilibrium between the number of molecules passing into and out of the liquid is temporarily destroyed.

Now more vapor molecules will enter the liquid than leave the liquid. Hence, the more rapidly moving vapor molecules enter the liquid—tending to increase the temperature of the liquid and decrease that of the vapor. But heat is being withdrawn from the liquid. Hence, the liquid temperature is not increased by the entering vapor molecules but the liquid temperature remains constant until the vapor and liquid attain the same temperature. By this time enough vapor molecules have entered the liquid (in excess of those which have left the liquid) to decrease the temperature of the vapor to such a point that equilibrium is again restored—the number of molecules entering and leaving the liquid is again the same. But, during this process, more molecules have been entering the liquid than have been leaving it. Hence, a portion of the vapor has been condensed.

310. Two Or More Vapors, When Mixed, Do Not Affect The Saturation Point Or Vapor Pressure Of Either provided the vapors do not act chemically on one another nor mix by solution (Sec. 169) when condensed. The presence of more than one vapor simply has a retarding effect on the time necessary for a vapor to become saturated. The same amount of liquid will evaporate into an air-filled space as into a vacuum of the same volume. The air merely retards the rate of evaporation.

Explanation.—The molecules of any gas or vapor have considerable space between them. The molecules of the second vapor occupy portions of these empty spaces. It is evident, from the theory of molecular

motion of gases, that the molecules in vaporizing from a liquid must encounter opposition by colliding with the molecules of the second vapor. Hence, due to the thus retarded motion, the time necessary for sufficient molecules to pass from the liquid to produce saturation is increased. It follows that complete saturation of a space wherein a partial vacuum exists is accomplished with greater rapidity than where the space is filled with air or other gas.

311. The Effect Of The Air In Retarding The Rate Of Evaporation is important. If water vapor, which is constantly evaporating from river, lake, and ocean, diffused rapidly, the atmosphere would always be completely saturated (100-per cent. humidity, Sec. 331). All absorbent objects about us would then be soaked continually with moisture. But, because of its very slow dissemination, relatively little water vapor is contained in the atmosphere—even in regions adjacent to large bodies of water. A portion of that water vapor which does exist in the atmosphere always condenses (Sec. 339) when the temperature falls to the saturation point (Sec. 305). Some one of the weather phenomena described in Sec. 339 then results.

312. The Combined Pressure Of Two Or More Vapors Or Gases Which Occupy The Same Space Is Equal To The Sum Of The Individual Pressures Exerted By Each.—This is the second of Dalton's laws (Sec. 306). Its truth may be readily verified experimentally as is explained below:

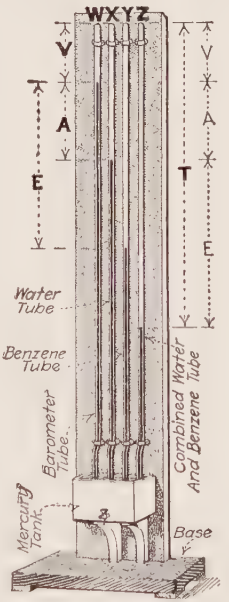


Fig. 303.—The combined pressure of two vapors is equal to the sum of their individual pressures.

Example.—In Fig. 303, W is an ordinary barometer tube with the usual vacuum space, of length V, above the mercury. All of the tubes W, X, Y, and Z are of identical construction. Into the space above the mercury in X enough water has been introduced to produce a saturated vapor, lowering the mercury level by distance A. Similarly, benzene vapor in Y lowers the level by distance E. Now, if an excess of water and of benzene were introduced into Z, the two combined saturated vapors would lower the mercury by distance T. Now it will

be found that: $T = V + A + E$ (nearly). This proves that the combined pressure of the water vapor and the benzene vapor is nearly equal to the sum of their individual pressures.

313. Boiling Or Ebullition Is Vaporization From Within The Body Of A Liquid as well as from its surface. When heat is applied (Fig. 304) to a glass vessel which contains a transparent liquid, as clean water, bubbles will, after a time, be seen to form in that portion of the liquid which is immediately contiguous to the source of heat. These bubbles are composed of vapor, in precisely the same form as that which is generated by evaporation (Sec. 296) at the surface of the liquid.

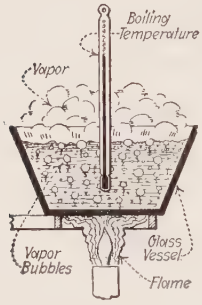


FIG. 304.—Illustrating boiling or internal vaporization.

EXPLANATION.—The liquid in contact with the bottom of the glass vessel (Fig. 304) absorbs heat from the gas flame. The vibratory motion (Sec. 45) of the molecules in this portion of the liquid mass is thereby intensified. Certain molecules attain very high velocities and, colliding, are thus "bounced" to comparatively great distances from one another. Certain of these separated molecules then assemble in groups and assume the mutual arrangement which is peculiar to the vaporous condition of matter. The bubbles, which may be seen through the transparent wall of the vessel, are the visible manifestation of this arrangement. Being less dense—lighter—than the surrounding liquid, these bubbles, or groups of vaporized molecules, tend (Sec. 137) to rise toward the upper surface. That is, a condition of boiling or ebullition ensues.

If the liquid mass is of considerable depth, the bubbles which are first formed may disappear before they reach the upper surface. When this happens, the bubbles have simply given up the heat, to which they owe their vaporous form, to the molecules of the cooler portions of the liquid through which they have passed. They have (Sec. 162) condensed. That is, they have resumed the molecular arrangement peculiar to the liquid state.

Due to this process of convection (Sec. 137) the entire mass of the liquid presently acquires a practically uniform temperature. Hence, the bubbles which are subsequently formed at the bottom of the vessel will retain their heat and, incidentally, their vaporous structure until they rise to the upper surface where they will break and their vapor will then mingle with the vapor above.

NOTE.—ALL OF THE BUBBLES WHICH FORM IN A BOILING LIQUID MAY NOT BE VAPOR BUBBLES.—Some of them may be due to the presence of

air in the liquid. Application of heat to an air-impregnated liquid will cause minute masses of the air to expand and form bubbles.

Note.—When A Liquid Boils The Molecules Pass Into The Vaporous Condition Both At The Free Surface Of The Liquid And At The Surfaces Of The Vapor Bubbles within the liquid. Thus, there is an essential difference between boiling and evaporation. In evaporation (Sec. 296) the molecules pass to the vaporous condition only at the free surface. The only reason (Millikan & Gale) why vaporization takes place so much more rapidly at the boiling temperature than just below it is that the bubbles first form at the boiling temperature and the evaporating surface is increased enormously by the bubbles as soon as they form.

314. Table Showing Boiling Temperature Of Liquids At Atmospheric Pressure. See Table 350 for boiling temperature of various liquefied gases. (Marks' Mechanical Engineers' Handbook.)

Liquid	Temperature, in deg. Fahr.	Liquid	Temperature, in deg. Fahr.
Zinc	1,680	Aniline	363
Sulphur	823	Calcium chloride (sat. sol.)	356
Mercury	675	Turpentine	320
Paraffin	572	Toluene	230
Glycerine	554	Sodium chloride (sat. sol.)	226.4
Phosphorus	554	Water	212
Linseed oil	538	Alcohol	172.4
Naphthalene	424	Helium	−450

315. Every Liquid Has, For A Given Impressed Pressure, A Definite Boiling Temperature.—When a thermometer is inserted in a mass of liquid to which heat is being applied (Fig. 304), the mercury will rise until the liquid begins to boil. The mercury—temperature—will then become stationary and will stay so (as long as there is liquid in the vessel and the pressure on the surface of the liquid remains constant) no matter how great the rate of heat application. Why the temperature thus remains constant is explained in Sec. 96 and Sec. 98. For a given liquid and a given pressure, this boiling temperature or boiling point is always the same; see Table 314.

Note.—The Reason The Temperature Of The Liquid Cannot Be Increased Above The Boiling Point is that the area of surface of the bubbles always increases to just such an extent that the loss of heat necessary to do the disgregation work which is required to affect vaporization is exactly equal to the heat received from the fire. In other words, the disgregation heat continually passing out with the ascending vapor molecules becomes just equal to the heat which is being continually supplied by the heat source. Thus, constant temperature and a *heat balance* are maintained.

316. The Boiling Temperature Is The Temperature At Which The Pressure Of The Saturated Vapor Equals The Pressure Existing Outside Of And Imposed On The Surface Of The Liquid.—This pressure is, when the vessel is wide open to the air, the atmospheric pressure. When the vessel is closed, the pressure is that due to the liquid vapor (usually steam) in the vessel plus the pressure of the air or any other gas which may be present.

Example.—When a steam boiler is first placed in operation and has air in its steam space, the air pressure imposed on the water surface may be considerable (up to atmospheric pressure). But after the boiler has been operated for a short time, practically all of the air is displaced and the pressure then imposed on the liquid surface is due almost wholly to the vapor pressure of the liquid.

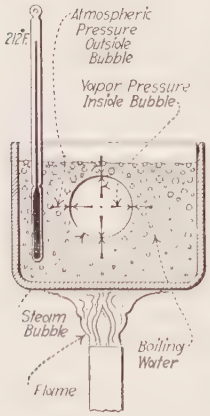


Fig. 305.—Vapor pressure within steam bubble equals pressure imposed on outside of bubble.

Explanation.—As stated previously, the formation of vapor bubbles is the visible manifestation of and is essential to boiling. Now it is evident that the vapor pressure of the vapor (Fig. 305) within each bubble must (disregarding the small additional impressed pressure due to the thrust of the liquid itself) be the same as the pressure—often the atmospheric pressure—which presses on the surface of the liquid. The inside vapor pressure and the outside impressed pressure must exactly equal each other—otherwise the bubble would collapse. Now (Sec. 315) a certain definite temperature is required for the production of each vapor pressure. Therefore it is evident that bubbles cannot form until the temperature of the liquid is such that the pressure which its vapor exerts is exactly equal to the impressed pressure. Hence, the boiling temperature of a liquid—the temperature of bubble formation—must be that temperature at which the vapor pressure equals the impressed pressure.

317. The Effect Of Change Of Pressure On The Boiling Points Of Liquids (See Table 318) will now be considered. If a boiling liquid is subjected to additional pressure, the boiling will cease and the temperature will again rise as the

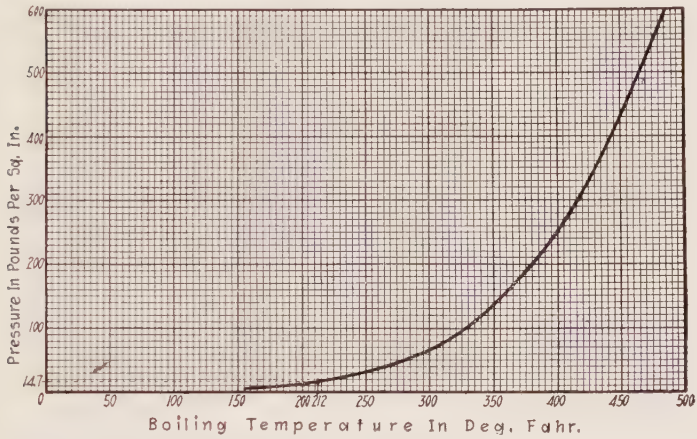


Fig. 306.—Graph showing relation of boiling temperature of water to pressure.

application of heat is continued. Ultimately, a new temperature—which corresponds to a new pressure—will be attained at which boiling will again commence. The greater the pressure the greater the boiling point (Fig. 306) and vice versa.

Example Of The Effect On Boiling Temperature Of Increasing The Pressure.—In Fig. 307, heat is imparted to water in *A*. Thereby the water in this cylinder is boiled. In the end of the cylinder fits a piston, *P*, which has sufficient weight to maintain a pressure of about 5 lb. per sq. in. gage within the cylinder. The sliding piston maintains the pressure constant. When the heating is begun, the piston rests on the surface of the cool water and the thermometer, *T*, indicates a low temperature—the temperature of the cool water. As the heating is continued, the temperature rises to about (see steam table, Sec. 394) 228° F., which corresponds to a pressure of 5 lb. per sq. in. At this temperature boiling commences. No further rise in temperature is indicated by the thermometer nor does the pressure, as shown by the gage, *G*, increase. But as the vapor which is projected from the boiling water collects above it, more and more space is required by the vapor. This pushes the piston up in the cylinder until, if permitted to continue, it would force the piston out of the top. But the pressure and temperature remain constant.

Now, suppose that after the boiling, as shown in A, has continued for a time, the pressure within the cylinder is so increased by the addition of weight, W, that the gage will indicate constantly 10 lb. per sq. in.

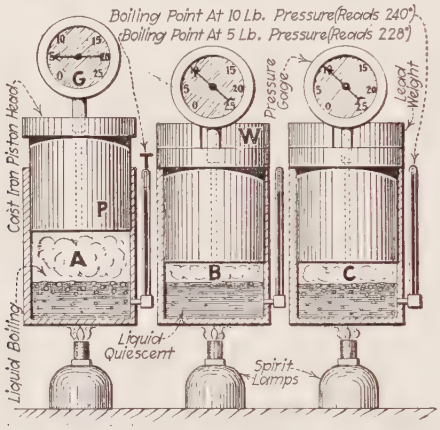


Fig. 307.—Illustrating effect of pressure on boiling points of liquids.

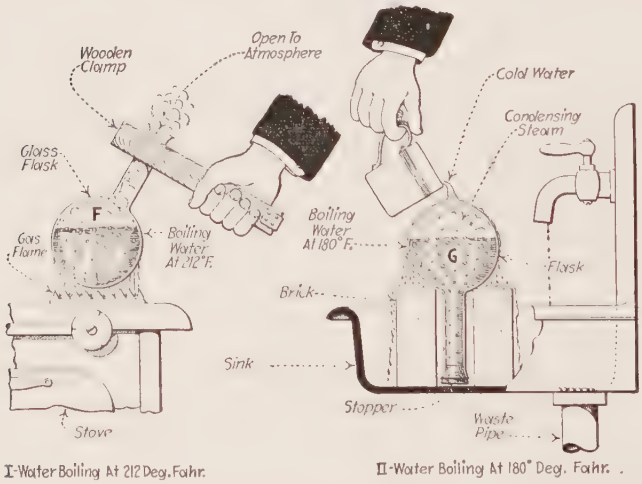


Fig. 308.—Experiment proving that the boiling point decreases as the pressure is decreased.

Immediately, the piston, which it will be assumed is resting half-way up in the cylinder, will be forced down. This reduces the volume of the vapor and, hence, increases its pressure. Due to this increased pressure,

boiling at once ceases—there will be no vapor bubbles in the liquid in *B*. But, if the heating of *B* is continued, ultimately the new boiling temperature of about 240° F. (see steam table), which corresponds to the new pressure of 10 lb. per sq. in., will be attained as shown at *C*. Then,

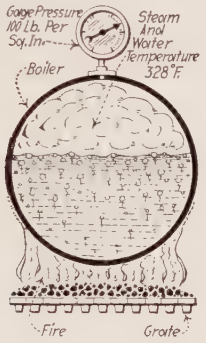


Fig. 309.—Illustrating effect of pressure on the boiling temperatures of liquids.

Fig. 310.—Graph showing variation of boiling temperature of water in accordance with variations of altitude above sea level.

the piston will again commence to rise as the boiling once more starts. Again, under these new conditions, the new temperature and the new pressure will remain constant.

Example Of The Effect On Boiling Temperature Of Decreasing The Pressure.—First, the water in the flask *F* (Fig. 308) is boiled.

Then the flask is removed from the flame, corked, and inverted as at *G*. The temperature of the hot water in the flask soon falls to below 212° F. and the boiling ceases. But if now some cold water be poured over the flask, as shown, the water in the flask will commence to boil again. The cold water by condensing the steam in the flask decreases the impressed pressure. Thereby the water in the flask boils at a temperature lower than 212° F. But when sufficient vapor has been evolved in the flask to produce the vapor pressure which corresponds to the new lower temperature, the boiling ceases. This process of boiling and condensation may be repeated many times at successively lower temperatures, without reheating, by repeated water applications.

Example.—Water in a steam boiler, under ordinary atmospheric pressure, or 14.7 lb. per sq. in., boils (Table 318 or any steam table and Fig. 306) at 212° F. When the water has vaporized into steam until

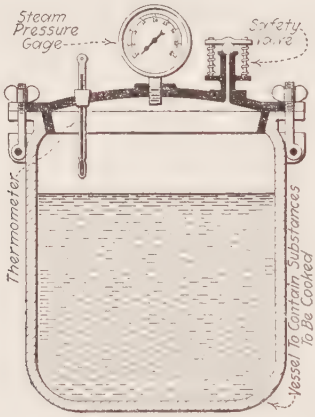


Fig. 311.—Pressure steam cooker. (Boiling of the water in the tightly-closed vessel generates steam, which is not permitted to escape. The steam increases the pressure within the vessel and thus raises the boiling point.)

(Fig. 309) a pressure of 100 lb. per sq. in. gage is attained, the boiling temperature is then, as shown by any steam table (Sec. 394) 328° F.

Examples. -Water in an open vessel will boil on the top of a high mountain at a much lower temperature (Table 319 and Fig. 310) than at sea level. This is because of the lower atmospheric pressure (Sec. 9) at the high altitude. It requires a long time to cook eggs or vegetables by boiling on a high mountain top because of the low boiling temperatures at high elevations. This difficulty may be overcome by boiling the food in a closed vessel or in a pressure cooker (Fig. 311) whereby the boiling point of the contained liquid is raised by the self-generated internal pressure.

318. Table Showing Boiling Temperatures Of Water At Various Pressures. (From Marks and Davis' STEAM TABLES.)

[a] Pressure, in lb. per sq. in.		Boiling temperature, in deg. Fahr.	[a] Pressure, in lb. per sq. in.		Boiling temperature, in deg. Fahr.
Absolute	Gage		Absolute	Gage	
1	− 13.7	101.8	100	85.3	327.8
5	− 9.7	153.0	150	135.3	358.5
10	− 4.7	193.2	200	185.3	381.9
14.7	0.0	212.0	250	235.3	401.1
15	0.3	213.0	300	285.3	417.5
25	10.3	240.1	400	385.3	444.8
50	35.3	281.0	500	485.3	467.3
75	60.3	307.6	600	585.3	486.6

[a] *Absolute Pressure* = *Gage Pressure* + 14.7. *Gage Pressure* = *Absolute Pressure* − 14.7. The equations are true only when the pressures are expressed in pounds per square inch. See Sec. 18 for equations and explanation.

319. Table Showing Average Boiling Temperatures Of Water At Various Altitudes Above Sea-level. It should be understood that, at any elevation, the barometric pressure varies from time to time. At all times, the actual boiling point of water is that corresponding to the atmospheric or barometric pressure and may be accurately found in any steam table (Sec. 394).

Altitude, in feet	Boiling temperature, in degrees Fahrenheit	Altitude, in feet	Boiling temperature, in degrees Fahrenheit
−1,316 (Dead Sea)	214	4,130	204
− 505	213	5,185	202
0 (Sea level)	212	6,250 (Mt. Washington)	200
510	211	8,950	195
1,020	210	11,720	190
1,545	209	15,650 (Mont Blanc)	184
2,050	208	17,337 (Himalayas)	180
3,085	206		

320. The Boiling Temperature Of A Liquid Which Holds Another Substance In Solution may be either above or below the boiling temperature of the pure liquid. If the dissolved substance is a solid, the boiling temperature will be higher than that of the pure liquid. But if the liquid holds a gas or a more volatile liquid in solution, the boiling temperature will be lower.

Example.—When a quantity of water (*A*, Fig. 312) has dissolved (Table 321) as much salt as it can possibly hold in solution the boiling

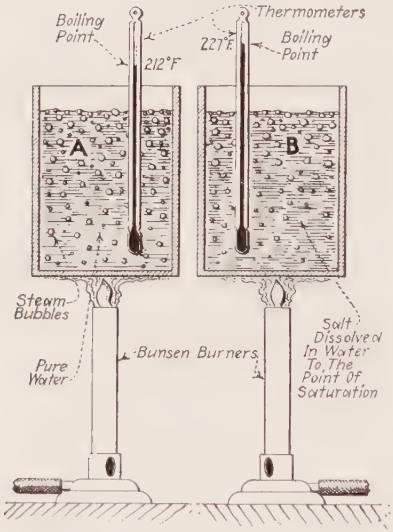


Fig. 312.—Illustrating the elevating effect of a dissolved solid on the boiling point of a liquid substance.

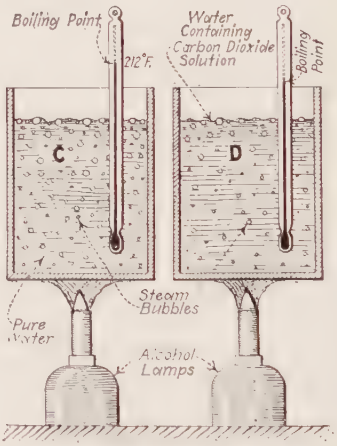


Fig. 313.—Illustrating the depressing effect, of a dissolved gas, on the boiling point of a liquid substance. (Steam bubbles only rise from the pure water whereas both steam and carbon dioxide bubbles rise from the solution.)

temperature at atmospheric pressure of the resulting brine (*B*, Fig. 312) will be about 227° F. When a quantity of water (*C*, Fig. 313) holds carbon-dioxide gas in solution, the boiling temperature of the solution (*D*, Fig. 313) will be less than 212° F.

321. Table Showing Boiling Temperature Of Brine At Different Degrees Of Saturation.—Computed from SMITHSONIAN TABLES.

Units by weight of salt to 100 units of water	Temperature, deg. Fahr.
6.6	212
12.4	215.6
17.2	217.4
21.5	219.2
25.5	221
33.5	222.8
40.7	227.8

322. The Latent Heat Of Vaporization is, generally speaking, the heat which is (Sec. 106) required to change a liquid at a given temperature into a vapor at the same temperature. A very great quantity of heat is necessary to effect vaporization although no temperature change occurs. Specifically: The latent heat of vaporization of a liquid is the number of B.t.u. (Table 323) which is absorbed and necessary—to change 1 lb. of the liquid into vapor at the *same* temperature and pressure. (Refer to Sec. 289 for a discussion of latent heat of fusion which is a somewhat similar property.) See preceding explanation (Sec. 104) of how the heat expended in vaporization is largely employed in doing disgregation work—but some of the heat may also be expended in doing external work as is there explained.

EXAMPLE.—Consider a closed vessel (Fig. 314) which has an escape valve, *V*, so adjusted that any vapor generated within the vessel will pass out at precisely the requisite rate to preserve a constant absolute pressure (Sec. 15) within the vessel of 14.7 lb. per sq. in. This is equivalent to 0.0 lb. per sq. in. gage pressure (Sec. 16). Exactly the same conditions would obtain if the vessel were located at the sea level (Sec. 9) and were open to the atmosphere.

Now, 1 lb. of water at 32° F. is placed in the vessel. It is heated with the spirit-lamp, *L*, flame. The mercury column in the thermometer will rise gradually until 180 B.t.u.—*MN*, Fig. 315—of heat (vibration heat)

have been imparted to the liquid. The thermometer will then read 212° F. (Each B.t.u. will raise the temperature of the 1 lb. of water 1° F. Hence, 180 B.t.u. will increase it by 180° F. Therefore, the resulting temperature will be 32 + 180 = 212° F.) This increase in temperature

Fig. 314.—Vaporizing water under constant pressure.

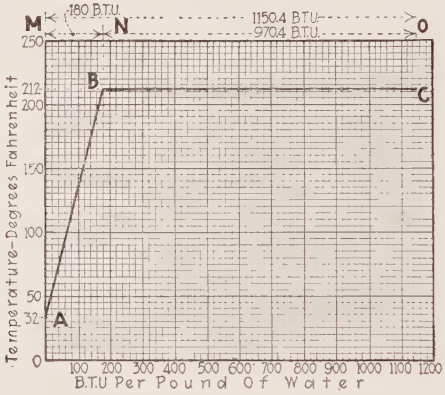


Fig. 315.—Illustrating latent heat of vaporization of 1 lb. of water.

is shown by *AB* in Fig. 315. The increase in temperature is due to vibration work (Sec. 97) which has been done by the heat on the water.

When the water temperature attains 212° F. the imparted heat will commence to do disgregation work (Sec. 98) and the water will commence to boil—vaporize—because the boiling point of water at atmospheric pressure (14.7 lb. per sq. in.) is 212° F. Now as the lamp, *L*, continues to impart heat to the water, the heat will continue to do disgregation work and vaporization will continue. That is, steam will start forming when the water temperature first attains 212° F. and its formation will continue so long as heat (disgregation heat) is being imparted to the water. But while this vaporization ensues the temperature of the water will not rise above 212° F. (*BC*, Fig. 315) in spite of the fact that heat is being added continually to the water. The thermometer will stand stationary at the 212° mark until the water has been entirely changed into water vapor or steam. This is indicated by the line *BC* in Fig. 315. There will be required, so repeated experiments show, 970.4 B.t.u. (*NO*, Fig. 315) to change the 1 lb. of water at 212° into 1 lb. of steam at 212°.

The heat required (970.4 B.t.u. in this case) to change 1 lb. of the liquid at boiling temperature into vapor at the same temperature is the latent heat of vaporization of the liquid.

If the heating is continued, at the instant the last trace of the original 1 lb. of water flashes into steam, the thermometer mercury will begin to

rise. The temperature rise will be due to the heat—vibration heat—which is absorbed by the steam and which will now manifest itself partly as vibration work (Sec. 97). That is, the steam becomes superheated (Sec. 356).

EXPLANATION.—Although the thermometer in Fig. 314 indicated no temperature rise while the vaporization was in progress, heat was, nevertheless, being transmitted continually from the flame to the water. But the energy of this latent (Sec. 106) or apparently inactive heat was spent partly in the work of disintegrating the molecular structure of the liquid molecules and in building up the new vapor-molecule structure (disgregation work, Sec. 98) and partly in expanding the molecules against external forces—the atmospheric pressure in this case (external work, Sec. 99). Therefore, this latent heat resides in the vapor in the form of potential molecular energy. It is transformed into the potential energy (Sec. 25) of position which the vapor molecules possess by virtue of their increased distance from one another. This phenomenon is similar to that of latent heat of fusion (Sec. 289) and is present in the vaporization of all substances.

EXAMPLE.—How much heat will be required, at atmospheric pressure, to vaporize 10 lb. of mercury which is at a temperature of 40° F.?

SOLUTION.—From Table 314, the boiling or vaporizing temperature of mercury is 675° F. From Table 90, the average specific heat of mercury is 0.033. Therefore, the heat necessary to raise the temperature of the 10 lb. of mercury from 40° F. to its vaporizing temperature is: $(675 - 40) \times 10 \times 0.033 = 218.6$ B.t.u. From Table 323, the latent heat of vaporization of mercury is 122 B.t.u. per lb. Therefore, to vaporize the 10 lb., there would be required: $10 \times 122 = 1{,}220$ B.t.u. Hence, the total heat necessary to raise the temperature and vaporize would be: $218.6 + 1{,}220 = 1{,}438.6$ B.t.u. Note that the greatest part of the total heat is necessary to effect vaporization and that comparatively little is used in raising the temperature of the mercury to the vaporizing point.

EXAMPLE.—How much heat will be required to: (1) Convert into water, a 201.5-lb. block of ice which is at 29° F.; (2) Raise the temperature of the resulting water to the boiling point at atmospheric pressure; (3) Vaporize the water under atmospheric pressure?

SOLUTION.—In an example under Sec. 292 it is shown that 29,186 B.t.u. are necessary to convert the 201.5 lb. of ice into water at 32° F., which is the melting temperature of ice. Now, from Table 90, the mean specific heat of water is 1.0. Also, from Table 314, the vaporizing temperature of water at atmospheric pressure is 212° F. Therefore, to raise the 201.5 lb. of water to the vaporizing temperature there would be required: $(212 - 32) \times 1.0 \times 201.5 = 36{,}270$ B.t.u. Since, the latent heat of vaporization of water at atmospheric pressure is (Table 323) 970.4 B.t.u. per lb., to vaporize this 201.5 lb. of water, there would be necessary: $201.5 \times 970.4 = 195{,}536$ B.t.u. Then, the total heat expenditure for melting the ice, raising the temperature of the water and vaporizing it is: $29{,}186 + 36{,}270 + 195{,}536 = 260{,}992$ B.t.u.

NOTE.—THE LATENT HEAT OF VAPORIZATION OF A LIQUID DIMINISHES AS THE TEMPERATURE AND PRESSURE, UNDER WHICH THE VAPORIZATION OCCURS, INCREASE.—It disappears entirely when (Sec. 349) the critical temperature and pressure are reached. See the vapor tables in Div. 11 for values.

323. Table Of Latent Heats Of Vaporization At Atmospheric Pressure. (MARKS' MECHANICAL ENGINEERS' HANDBOOK)

Material	Latent heat of vaporization, in B.t.u. per lb.	Material	Latent heat of vaporization, in B.t.u. per lb.
Acetone	233	Hydrogen	222
Alcohol	385	Methyl chlorine	175
Aniline	198	Mercury	122
Benzol	169	Nitrogen	81.5
Carbon bisulphide	152.5	Oxygen	92
Chlorine	112	Sulphur	650
Chloroform	110	Turpentine	126
Ether	162	Water	970.4

324. The Latent Heat Of Steam is the latent heat of vaporization (as defined above) of water and is equal to 970.4 B.t.u. at atmospheric pressure—14.7 lb. per sq. in. absolute—and the corresponding temperature of 212° F. See steam table 394 for other temperatures and pressures.

325. The Latent Heat Of Vaporization May Be Divided Into Two Parts: (1) *External latent heat of vaporization.* (2) *Internal latent heat of vaporization.* Both are defined below. Both of these latent heats are stored in the vapor and are given out when the vapor is condensed under the same external conditions as those under which it was vaporized. Values for these two heats, for the common vapors, are given in the tables in Div. 11. Thus:

$$L = L_E + L_I \qquad (241)$$

(B.t.u. per lb.)

Wherein: L = latent heat of vaporization, that is, the total latent heat of vaporization, in British thermal units per pound. L_E = external latent heat of vaporization, in British thermal

units per pound. L_I = internal latent heat of vaporization, in British thermal units per pound.

326. The Internal Latent Heat Of Vaporization, L_I, is the *disgregation* heat which must be added to the liquid to vaporize it, or which is given up by the vapor when it is liquefied. It is the heat energy which is expended in the internal work of overcoming the molecular cohesion of the liquid molecules which is necessary to change them into vapor molecules. It is the increase in internal heat energy which accompanies vaporization. As is shown by the values in the tables of vapor properties in Div. 11, the internal latent heat of vaporization decreases as the temperature, at which the vaporization occurs, increases. This is because the higher the temperature the more rapidly the molecules will be vibrating and the further they will be apart; hence, less heat will be required to disgregate into a vapor a liquid at a high temperature than will be required for a liquid at a low temperature.

327. The External Latent Heat Of Vaporization, L_E, is the *external-work heat* which must be added to the liquid to vaporize it or which is given up by the vapor when it is liquefied. It is the heat energy which must be expended in overcoming the resistance of external forces to the increase of volume of a liquid substance, which is incident to its vaporization. It is equivalent to the mechanical work done by the substance in expanding from the liquid state to the vapor condition of the gaseous state. See explanation below.

EXPLANATION.—Consider a cylinder (Fig. 316) which has an internal sectional area of 1 sq. ft. and which is somewhat over 26.8 ft. high. The cylinder stands open in the atmosphere—which imposes on it an absolute pressure of 14.7 lb. per sq. in. Suppose that 1 lb. of water at a temperature of 212° F. is placed in the cylinder, as at *I*. Now add heat and vaporize this 1 lb. of water. Experiment will show (see Steam Table 394 in Div. 11), that it will require 970.4 B.t.u. (the latent heat of vaporization) to vaporize the 1 lb. of water at 212° F. into steam at 212° F. Now, the steam thus formed will, so experiment shows, force the air out of the cylinder *I* against the atmospheric pressure of 14.7 lb. per sq. in. (2,117 lb. per sq. ft.) and will exactly fill the cylinder—as in Fig. 316-*II*—which has a volume of 26.8 cu. ft.

The external work done, by the expansion of the water into steam, under atmospheric pressure, will be: *Force* × *Distance* 2,117 × 26.8 = 56,376 *ft.-lb.* Now, this external work done by the steam in expanding

accounts for only a small part of the total latent heat of 970.4 B.t.u. which was expended in changing the liquid into a vapor. Thus: 56,736 *ft.-lb.* ÷ 778 = 72.8 *B.t.u.* = *external latent heat of vaporization. The*

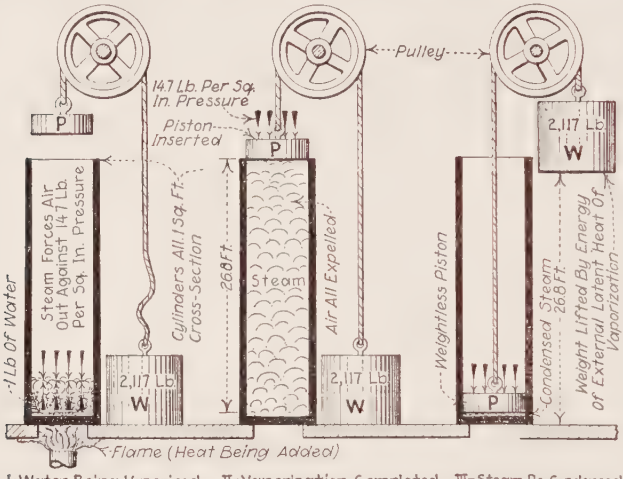


Fig. 316.—Showing external latent heat of vaporization converted into mechanical work.

remainder: 970.4 − 72.8 = 897.6 *B.t.u.* = *internal latent heat of vaporization* and is heat which was expended in disgregation work.

The external work done by the vaporization might be recovered if, (Fig. 316-*II*) a tight piston *P* is inserted in the cylinder and the 1 lb. of steam be cooled so that it will contract (condense) back into 1 lb. of water at 212° F. as at *III*—Fig. 316. Then the atmospheric pressure would force *P* down, lifting *W*. *W*, which weighs 2,117 lb., would be lifted 26.8 ft., because 2,117 × 26.8 = 56,736 *ft.-lb.*; all friction losses are here neglected. Thus the external work done during the vaporization would be recovered. This is one of the principles the application of which renders useful a condenser (Sec. 513) on a steam engine or turbine.

328. When A Liquid Is Vaporized, The Latent Heat Of Vaporization Required Therefor Is Abstracted From Surrounding Objects.—Thus vaporization is, in reality, a cooling process. The heat thus required may be taken from the flame of a lamp (Fig. 307) or from the flame of a coal fire under a steam boiler. Or, as explained in preceding Sec. 300, the heat may be drawn from the liquid itself, thereby cooling the liquid. This principle is utilized practically in a number of useful ways, the most important of which have been mentioned in Sec. 293.

329. When A Vapor Condenses, Its Latent Heat Of Vaporization Is Given Up To Surrounding Objects.—Condensation is defined and discussed briefly in preceding Sec. 162. Thus, when 1 lb. of vapor is condensed due either to increased pressure or decreased temperature or both, it releases the number of B.t.u. (Sec. 322) which is equivalent to its latent heat of vaporization. With a given pressure, condensation takes place at the same temperature at which vaporization occurs.

Example.—The heat given out (Fig. 317) by a steam-heating system (Div. 17) is almost wholly heat which is released by the condensation of steam in the radiators and then transmitted through their walls to warm the air of the room.

Example.—In condensers for steam power plants and other services, the steam or vapor is condensed by cooling it, usually with cold water. The latent heat of vaporization thus released is absorbed by the cooling water and raises its temperature.

Example.—Closed tank K in Fig. 318 is of such size that it will contain exactly 1 lb. of steam at 0.0 lb. per sq. in. gage pressure—or 14.7 lb. per sq. in. absolute pressure. That is, it will contain 1 lb. of steam at atmospheric pressure. The tank is fitted with an automatic air-inlet valve, B, or vacuum beaker which opens to the atmosphere at the precise instant necessary to prevent

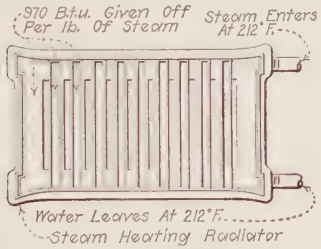


Fig. 317.—Showing heating with steam radiator through latent heat of vaporization.

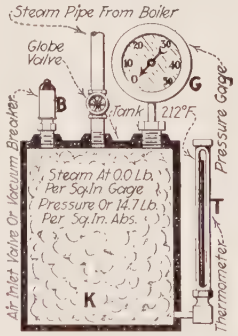


Fig. 318.—Condensing steam at a constant pressure.

formation of a partial vacuum by condensation of the steam. Thereby, the pressure within K is prevented from falling below 14.7 lb. per sq. in.

Now, 1 lb. of steam is admitted to K. The temperature T, of this steam, as shown by the steam table, is 212° F. The steam begins to cool. It gives up heat to surrounding objects as indicated by AB in Fig. 319. Immediately some of the steam condenses to water at 212° F. But the temperature of the remaining steam stays constant, as indicated by line AB, until 970.4 B.t.u. has been given up: The latent heat of steam at atmospheric pressure is 970.4 B.t.u. The remainder of the steam

condenses gradually. When exactly 970.4 B.t.u. have been given up, all of the steam will have condensed to water.

If heat be further abstracted from the water (*BC*, Fig. 319), its temperature will be decreased correspondingly. When 180 B.t.u. have been

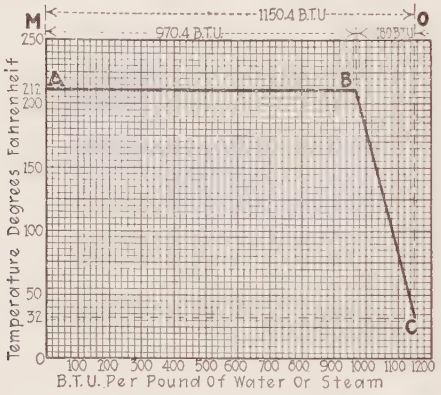


Fig. 319.—Illustrating latent-heat phenomenon in condensation of 1 lb. of steam.

abstracted, the temperature of the water will then be 32° F. This condensation process is just the reverse of the vaporization process which is described in connection with Figs. 314 and 315.

330. Atmospheric Air Contains oxygen, nitrogen, a little carbon dioxide, traces of other rare gases, and *water vapor.* The air is, therefore, a mixture of gases and water vapor. The water vapor is in the air principally as the result of evaporation from the surfaces of rivers, lakes, ponds, and from "moist" objects. The water vapor in the air is not, usually, in the saturated state. That is, the air can usually be cooled or compressed somewhat before the moisture (water vapor) in it is condensed. The term *humidity* is used to describe the condition of air which contains water vapor; see following section.

331. Atmospheric Humidity may be expressed in two different ways: (1) *The absolute humidity* (Table 332) which expresses the total weight of water vapor in a unit volume of air. (2) *The relative humidity*, which expresses the ratio which exists between the weight of vapor actually present in a unit volume of air to the weight that would be present if the vapor were

saturated at its actual temperature. This ratio is commonly denoted as a percentage of complete saturation.

332. Table Showing Absolute Humidities Or The Weights, In Grains Per Cubic Foot, Corresponding To Different Temperatures And Percentages Of Relative Humidity Of Aqueous Vapor In Atmospheric Air.

Air temperature, in deg. Fahr.	Percentage of relative humidity									
	10 %	20 %	30 %	40 %	50 %	60 %	70 %	80 %	90 %	100 %
−20	0.017	0.033	0.050	0.066	0.083	0.100	0.116	0.133	0.149	0.166
−10	0.028	0.057	0.086	0.114	0.142	0.171	0.200	0.228	0.256	0.285
0	0.048	0.096	0.144	0.192	0.240	0.289	0.337	0.385	0.433	0.481
10	0.078	0.155	0.233	0.310	0.388	0.466	0.543	0.621	0.698	0.776
20	0.124	0.247	0.370	0.494	0.618	0.741	0.864	0.988	1.112	1.235
30	0.194	0.387	0.580	0.774	0.968	1.161	1.354	1.548	1.742	1.935
40	0.285	0.570	0.855	1.140	1.424	1.709	1.994	2.279	2.564	2.849
50	0.408	0.815	1.223	1.630	2.038	2.446	2.853	3.261	3.668	4.076
60	0.574	1.149	1.724	2.298	2.872	3.447	4.022	4.596	5.170	5.745
70	0.798	1.596	2.394	3.192	3.990	4.788	5.586	6.384	7.182	7.980
80	1.093	2.187	3.280	4.374	5.467	6.560	7.654	8.747	9.841	10.934
90	1.479	2.958	4.437	5.916	7.395	8.874	10.353	11.832	13.311	14.790
100	1.977	3.953	5.930	7.906	9.883	11.860	13.836	15.813	17.789	19.766
110	2 611	5.222	7.834	10.445	13.056	15.667	18.278	20.890	23.501	26.112

NOTE.—The above table is an abstract from PSYCHROMETRIC TABLES by C. F. Marvin, published by the U. S. Weather Bureau, Washington, D. C., as Bulletin No. 235.

333. Humidity Of The Atmosphere is that condition of atmospheric air wherein it is more or less permeated with water vapor. Humidity is a universal and necessary attribute of the earths' atmosphere. Atmospheric air in one locality may be many times less humid—contain less water vapor—than in another. But nowhere will it be found entirely without water vapor. The humidity varies with the temperature. The cool air at the summit of a mountain is, generally, much less humid than the comparatively warm air in the valley at the mountain's base.

NOTE.—EXISTENCE OF A PROPER AMOUNT OF WATER VAPOR IN THE ATMOSPHERE IS ESSENTIAL to comfortable and hygienic living conditions,

both for plants and animals. For human beings, too much humidity is about as uncomfortable as too little. When the humidity is too low, one experiences a dry parched feeling. When it is too great, the "sticky" sensation, which occurs on damp hot days, is felt. In winter when the natural humidity within buildings is low due to the low humidity out of

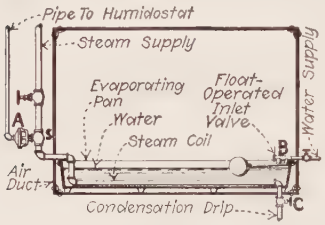


Fig. 320.

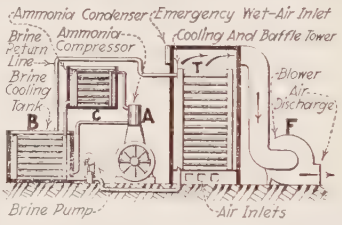


Fig. 321.

Fig. 320.—Cross section showing humidifying apparatus, or "humidifier," in air duct of ventilating system. (When the humidity becomes low, the humidostat, which is located in a room above, admits air pressure to diaphragm-valve *A*, thus opening steam valve, *S*.)

Fig. 321.—Elementary air drier for blast furnace. (Ammonia is compressed in *A*, condensed in *C*, and allowed to expand into *B*. Brine is circulated through *B* and *T*. Air is sucked by *F* through *T*, wherein it is cooled below the dew point, and the condensed vapor is removed, as water, by baffles.)

doors and the drying effect of the heating systems, the deficiency may be supplied (Fig. 320) by a *humidifier*. In certain manufacturing processes a definite humidity is quite necessary. A suitably-designed humidifier will provide it. In other processes, for which dry air is required, the moisture may be removed by a *dehumidifier*, or *air drier* (Fig. 321).

334. Relative Humidities May Be Determined By Means Of The Sling Psychrometer (Fig. 322) or wet-and-dry-bulb thermometer. The utility of this instrument is based upon the principle (Sec. 300) of cooling by evaporation. Evaporation of moisture from the muslin cloth which envelopes the bulb of thermometer *A* produces a cooling effect thereof which causes thermometer *A* to give a lower reading than thermometer *B*, the bulb of which is exposed directly to the air.

Explanation.—The muslin which envelopes the wet bulb (Fig. 322) is thoroughly saturated with water. The sling psychrometer is then whirled rapidly through the air for about one minute. This is to insure a rapid penetration of air among the fibers of the cloth around the wet bulb.

The difference between the indications of thermometers *A* and *B* is then noted. The one with the wet bulb will, generally, show a lower reading than the one with the dry bulb. This is due to the fact that, in general, the vapor in atmospheric air is not saturated. When there is no differ-

ence between the readings of thermometers A and B, the water vapor which is intermingled with the air is fully saturated.

The psychrometer is based on the law of evaporation (Sec. 298) that the rate of evaporation is greater into dry air than into air which contains vapor. The whirling of the thermometers causes the water on the wet bulb to evaporate

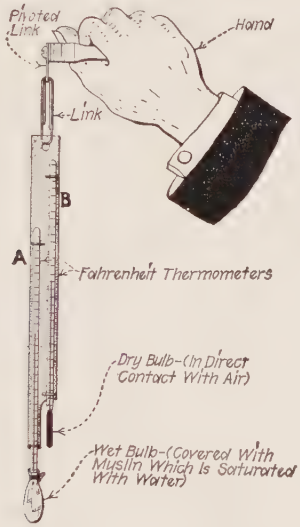


Fig. 322.—A sling psychrometer.

rapidly. The evaporation cools (Sec. 300) the thermometer and the water around its bulb. Evaporation and cooling continue until the water is cooled to the temperature at which its vapor pressure is just sufficient to keep driving off vapor molecules at a constant rate.

Now it can be shown that the relative humidity of the air is a function of the temperature-difference indicated by the wet- and dry-bulb thermometers of a sling psychrometer. Hence, when the temperature-differences are known, the corresponding relative humidities may be determined by consulting Table 335.

Example.—Suppose that air at a temperature of 70° F. is drawn into a building through the ventilating ducts. Also, suppose that a humidity test, made with a sling psychrometer (Fig. 322), shows a temperature difference, between thermometers A and B, of 17° F. Then, by Table 335, the relative humidity is 30 *per cent.* This value is found in the same horizontal row with 70, which is the given air-temperature, and in the same vertical row with 17, which is the given psychrometer-difference.

335. Table Showing Relative Humidities, In Per Cent., Corresponding To Various Wet- And Dry-bulb Temperature Differences (accurate for an atmospheric pressure of 14.25 lb. per sq. in. = 29-in. barometer).

Air temperature, in deg. Fahr.	Temperature-difference, in degrees Fahrenheit, between wet- and dry-bulb thermometers																				
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
32	100	90	79	69	60	50	41	31	22	13	4										
34	100	90	81	72	62	53	44	35	27	18	9	1									
36	100	91	82	73	65	56	48	39	31	23	14	6	0								
38	100	91	83	75	67	59	51	43	35	27	19	12	4								
40	**100**	**92**	**84**	**76**	**68**	**61**	**53**	**46**	**38**	**31**	**23**	**16**	**9**	**2**							
42	100	92	85	**77**	70	62	55	48	41	34	28	21	14	7	0						
44	100	93	85	78	71	64	57	51	44	37	31	24	18	12	5	0					
46	100	93	86	79	72	65	59	53	46	40	34	28	22	16	10	4	0				
48	100	93	87	80	73	67	60	54	48	42	36	31	25	19	14	8	3	0			
50	**100**	**93**	**87**	**81**	**74**	**68**	**62**	**56**	**50**	**44**	**39**	**33**	**28**	**22**	**17**	**12**	**7**	**2**	**0**		
52	100	94	88	81	75	69	63	58	52	46	41	36	30	25	20	15	10	6	0	0	
54	100	94	88	82	76	70	65	59	54	48	43	38	33	28	23	18	14	9	5	0	0
56	100	94	88	82	77	71	66	61	55	50	45	40	35	31	26	21	17	12	8	4	0
58	100	94	89	83	77	72	67	62	57	52	47	42	38	33	28	24	20	15	11	7	3
60	**100**	**94**	**89**	**84**	**78**	**73**	**68**	**63**	**58**	**53**	**49**	**44**	**40**	**35**	**31**	**27**	**22**	**18**	**14**	**10**	**6**
62	100	94	89	84	79	74	69	64	60	55	50	46	41	37	33	29	25	21	17	13	9
64	100	95	90	85	79	75	70	66	61	56	52	48	43	39	35	31	27	23	20	16	12
66	100	95	90	85	80	76	71	66	62	58	53	49	45	41	37	33	29	26	22	18	15
68	100	95	90	85	81	76	72	67	63	59	55	51	47	43	39	35	31	28	24	21	17
70	**100**	**95**	**90**	**86**	**81**	**77**	**72**	**68**	**64**	**60**	**56**	**52**	**48**	**44**	**40**	**37**	**33**	**30**	**26**	**23**	**20**
72	100	95	91	86	82	78	73	69	65	61	57	53	49	46	42	39	35	32	28	25	22
74	100	95	91	86	82	78	74	70	66	62	58	54	51	47	44	40	37	34	30	27	24
76	100	96	91	87	83	78	74	70	67	63	59	55	52	48	45	42	38	35	32	29	26
78	100	96	91	87	83	79	75	71	67	64	60	57	53	50	46	43	40	37	34	31	28
80	**100**	**96**	**91**	**87**	**83**	**79**	**76**	**72**	**68**	**64**	**61**	**57**	**54**	**51**	**47**	**44**	**41**	**38**	**35**	**32**	**29**
82	100	96	92	88	84	80	76	72	69	65	62	58	55	52	49	46	43	40	37	34	31
84	100	96	92	88	84	80	77	73	70	66	63	59	56	53	50	47	44	41	38	35	32
86	100	96	92	88	85	81	77	74	70	67	63	60	57	54	51	48	45	42	39	37	34
88	100	96	92	88	85	81	78	74	71	67	64	61	58	55	52	49	46	43	41	38	35
90	**100**	**96**	**92**	**89**	**85**	**81**	**78**	**73**	**71**	**68**	**65**	**62**	**59**	**56**	**53**	**50**	**47**	**44**	**42**	**39**	**37**
92	100	96	92	89	85	82	78	75	72	69	65	62	59	57	54	51	48	45	43	40	38
94	100	96	93	89	86	82	79	75	72	69	66	63	60	57	54	52	49	46	44	41	39
96	100	96	93	89	86	82	79	76	73	70	67	64	61	58	55	53	50	47	45	42	40
98	100	96	93	89	86	83	79	76	73	70	67	64	61	59	56	53	51	48	46	43	41
100	**100**	**96**	**93**	**90**	**86**	**83**	**80**	**77**	**74**	**71**	**68**	**65**	**62**	**59**	**57**	**54**	**52**	**49**	**47**	**44**	**42**
102	100	96	93	90	86	83	80	77	74	71	68	65	63	60	57	55	52	50	47	45	43
104	100	97	93	90	87	84	80	77	74	72	69	66	63	61	58	56	53	51	48	46	44
106	100	97	94	90	87	84	81	78	75	72	69	66	64	61	59	56	54	51	49	47	45

Note.—The Above Table Is An Abstract From Psychrometric Tables by C. F. Marvin, published by the U. S. Weather Bureau, Washington, D. C., as Bulletin No. 235.

336. Relative-humidity Determinations Are Of Much Practical Importance.—Forecasts of probable rain or frost are based by weather-bureau experts on relative-humidity observations. In many greenhouses the humidity is measured regularly. It is then systematically maintained at such values that the plants will thrive. In industrial, office, amusement, hospital, and residence buildings measurement and control of humidity may be desirable or necessary. In such buildings, the relative humidity should be about 50 to 60 per cent. In certain industrial operations lower or higher relative humidities are frequently necessary and are maintained.

337. Low Relative Humidity In Inhabitated Buildings Causes Colds And Wastes Fuel.—"Dry" air affects the respiratory organs adversely. Also, when the air is "dry" the evaporation of perspiration is rapid. The skin is cooled accordingly. Hence, with two rooms at the same temperature, a person will feel much warmer in the one wherein the humidity is high than in the one in which it is low. The fuel waste thus due to low interior humidities is estimated to be from 12 to 25 per cent.

Note.—Millikan And Gale State that "The average home that is heated to 72° F. by steam or hot water is estimated by health authorities to have a relative humidity of 30 per cent. With hot-air heating, it may be 25 per cent. This is less than the average humidity of extensive desert regions.

338. A Psychrometric Chart (Fig. 323) provides a means for determining graphically the relative and absolute humidities of atmospheric air and for solving many problems is *air conditioning*—that is, in regulating the temperature and humidity of the air.

Example.—If, in a room, the wet-bulb and dry-bulb temperatures are, respectively, 74 and 85° F., what are the relative and absolute humidities? Solution.—Following vertically upward from the dry-bulb temperature of 85° F. to the inclined line representing a wet-bulb temperature of 74° F., the relative humidity is found to be 60 *per cent.* Also, following upward from 85° F., mark on the lower scale to the curve *F* and then horizontally to the left to the scale *F*, it is found that saturated water vapor at 85° F. weighs 12.7 *grains per cu. ft.* Hence, the water vapor in air of 60 per cent. relative humidity at 85° F. will weigh: $0.60 \times 12.7 = 7.6$ *grains per cu. ft.*

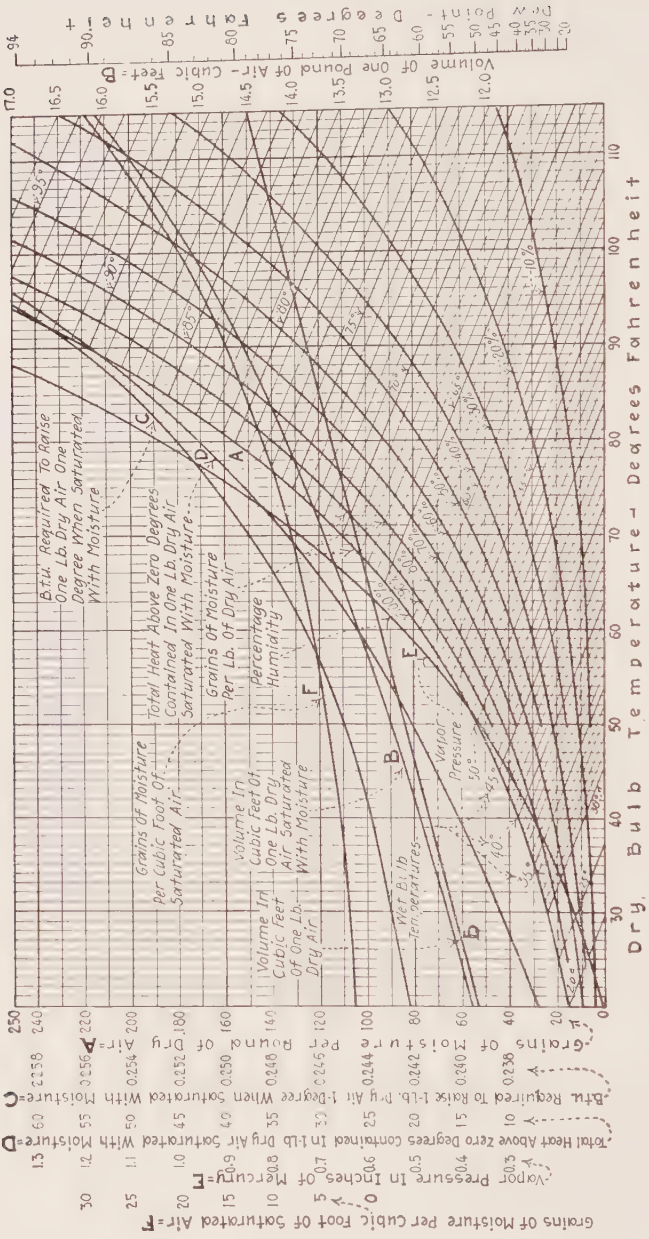

Grains Of Moisture Per Cubic Foot Of Saturated Air=F
Vapor Pressure In Inches Of Mercury=E
Total Heat Above Zero Degrees Contained In 1 Lb. Dry Air Saturated With Moisture=D
B.t.u. Required To Raise 1-Lb. Dry Air 1-Degree When Saturated With Moisture=C
Grains Of Moisture Per Round Of Dry Air=A
Dry Bulb Temperature - Degrees Fahrenheit
Volume Of One Pound Of Air - Cubic Feet=B
Degrees Fahrenheit - Dew Point
B.t.u. Required To Raise One Lb. Dry Air One Degree When Saturated With Moisture
Total Heat Above Zero Degrees Contained In One Lb. Dry Air Saturated With Moisture
Grains Of Moisture Per Cubic Foot Of Saturated Air
Volume In Cubic Feet Of One Lb. Dry Air
Volume In Cubic Feet One Lb. Dry Air Saturated With Moisture
Grains Of Moisture Per Lb. Of Dry Air
Percentage Humidity
Wet Bulb Temperatures
Vapor Pressure
A
B
C
D
E
F

Fig. 323.—See following page for explanation.

339. Dew, Rain, Hail, Frost, Sleet, Snow, Fog, And Clouds Are All The Result Of Condensation Of Moisture In The Atmosphere (the moisture or aqueous vapor is that produced by evaporation, Sec. 296). Which of these phenomena results is, as will be described, determined by the specific conditions under which the condensation occurs.

340. The Dew Point is the temperature at which the water vapor in the atmosphere becomes saturated (Sec. 305) and will condense or deposit as drops of water or dew.

Note.—The Dew Point Will Be Different For Different Absolute Humidities.—The greater the humidity the higher the dew point. The *relative* humidity at the dew point is always 100 per cent. As the temperature of atmosphere at 100 per cent. relative humidity decreases, there will be a certain condensation—production of dew—for each degree temperature decrease. But even if the air temperature is decreased to 32° F.—the freezing point of water—some moisture will remain in the air.

341. Dew is formed when—at night—the temperature of a thin layer of atmosphere, which lies close to the earth's surface, falls to the dew point. After the sun sets, the earth's surface and the objects on it lose heat by radiation. Thereby they are cooled to a temperature lower than that of the main body of the atmosphere, which cools more slowly. But the temperature of the relatively thin stratum of atmosphere (air and water vapor) immediately adjacent to the cooled earth's surface and to the objects on it—such as plants, stones, and earth—is reduced to the dew-point or somewhat below. Thereby dew is formed and deposited on the objects.

Note.—"Sweating" Occurs When Water Vapor Condenses on a cool surface which has reduced the temperature of the vapor to the dew point. Examples are the sweating of cold-water pipes in a warm

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Fig. 323.—Psychrometric chart (Barometric pressure—29.92 in. mercury column—reproduced by permission from the Carrier Engineering Corporation, Newark, N. J.) All temperatures are in degrees Fahrenheit. *Dry bulb temperatures* are represented by vertical lines with values indicated on lower edge of chart. *Wet bulb temperatures* are represented by oblique straight lines with values indicated on the lines. *Dew point temperatures* are represented by horizontal lines and their values indicated at the right. *Percentages of relative humidity* are represented by converging curved lines with values indicated between the oblique straight lines for 63° and 64° wet bulb temperature. *Any two of the above properties may be found if the other two are known.* First, find the point of intersection of the lines representing the given properties, and then follow through this point, the lines representing the unknown properties, and the values of the latter can be read from their respective scales.

humid room and that of the inner surfaces of window panes when it is warm and humid inside and cold outside. Essentially, *sweating is a dew formation. Sweating can be prevented* by causing a rapid circulation of air about the surface upon sweating tends to occur—the removal of the air (and vapor) from the cold surface is thus effected before its temperature has a chance to be cooled to the dew point. Sweating may also be prevented by covering the surface which tends to "sweat" with a heat-insulating (Sec. 114) material. This heat insulator will prevent the rapid transfer of heat from the warm vapor to the cool surface and thus minimize sweating.

342. Frost is formed if the condensation, as described under "dew," occurs upon a surface the temperature of which is lower than the freezing point of water. Windows become "frosted" in winter, when the outside temperature is considerably below the freezing point of water. It may be prevented just as is sweating (see preceding note).

343. Fog results if the cooling effect of the earth's surface (see "dew" above) is sufficient to decrease to the dew point the temperature of a rather thick stratum of atmosphere which lies adjacent to the earth. The water vapor in the atmosphere then condenses on the dust particles which are suspended therein and forms a fog.

344. Clouds result when, at a considerable distance above the earth's surface, the temperature of a body of water vapor in the atmosphere is decreased to the dew point. This may occur when a current of warm air passes into a cold upper region: The water vapor condenses around suspended dust particles and forms clouds.

NOTE.—RAIN is formed (Millikan and Gale) if the cooling is sufficient to free a considerable amount of moisture. Then the drops become large and fall. If this falling rain freezes before it reaches the ground, it is called *sleet*. If the temperature at which condensation begins is below freezing, the condensing moisture forms into *snowflakes* (Fig. 324). When the violent air currents which accompany thunder-storms carry the condensed moisture up and down several times through alternate regions of snow and rain, *hailstones* are formed.

345. Distillation is the process of separating the more volatile parts of a substance, from those less volatile, by vaporizing and subsequently condensing. For a liquid, it is done (Fig. 325) by first boiling the solution, *B*, and then condensing the resulting vapor in a separate vessel, *C*. By this means a

liquid may be freed from whatever solid substances (which do not vaporize at all) it may hold in solution. Or it may be freed from those liquid substances which vaporize at different temperatures (see fractional distillation, Sec. 346).

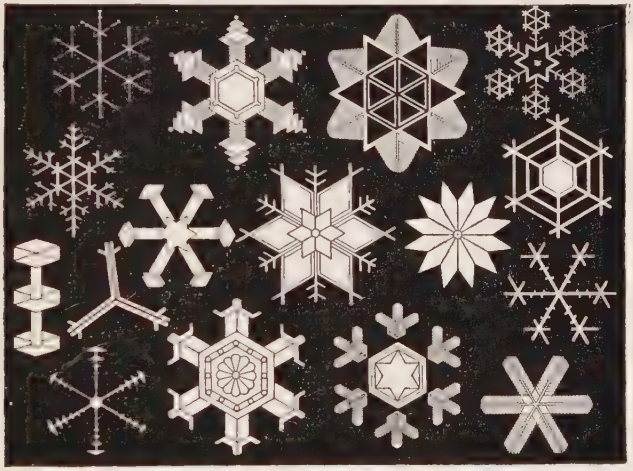

Fig. 324.—Snow-flake crystals.

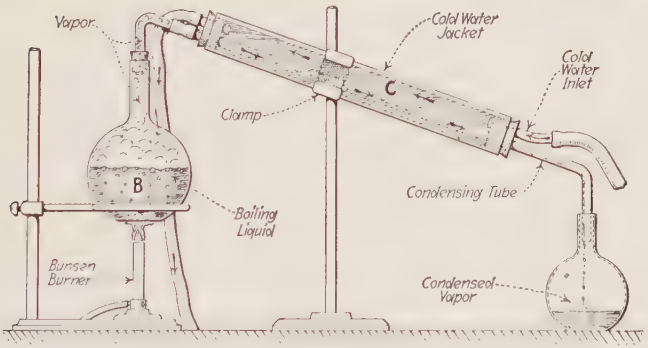

Fig. 325.—Illustrating the principle of distillation.

Example.—The water which is fed to a steam boiler usually holds mineral substances in solution. The water is vaporized by boiling. It is thus freed from the mineral substances. The water, in the form of steam, is conveyed from the boiler. The mineral substances, in the form of *scale* (Sec. 174), remain behind. The steam may be condensed in the radiators of a heating system. Then, provided there were no gaseous

nor highly volatile liquid, substances in the solution which was fed to the boiler, pure water will be drained from the radiators. Thus the process of distillation will be completed.

Note.—When Brine Or Salt-water Is Boiled, The Resulting Steam Contains No Salt.—Similarly, with many other liquid solutions, the vapor arising from the solution is free from the solid substances which were dissolved in the liquid.

346. Fractional Distillation is the process of separating different liquid substances which have different boiling temperatures, from one another. When both or several of the liquid constituents of a solution are volatile, the vapors of both or of all will each issue from the solution at its boiling temperature. (The boiling temperature of a solution of two or more liquids usually lies between the highest and the lowest boiling temperatures of any of the component liquids although it sometimes lies below that of either constituent.) But, the liquid which has the lower boiling temperature will supply most of the vapor. Hence by a prolonged distillation at gradually increasing temperatures different volatile liquids may usually be separated from the same solution.

Explanation.—The liquid which has the lower boiling point will predominate in the ensuing vapor. Thus, its concentration in the remaining liquid will gradually decrease and the remaining liquid in the boiler will gradually assume a higher boiling point. The first vapor that comes off will, when condensed, provide a solution which has a greater concentration of the more volatile liquid, than had the original solution. As the boiling point increases, less and less of the more volatile liquid is evaporated and condensed. Finally, a point is reached where the composition of the condensing vapor (if but two liquids were present in the original solution) becomes about the same as that of the original solution. At this point the distillation is either stopped or the distillate (condensed vapor) is led into a different vessel than was used up to this point. If a greater concentration of the more volatile liquid (than the first distillation provides) is desired, the first distillate is again subjected to a second distillation. In this way, by successive distillations, a product of almost any desired concentration may be effected.

Example.—Fractional Distillation Of Crude Oil Provides The Various Petroleum Products (Fig. 326) such as naphtha, benzine, gasoline, kerosene, and the lubricating oils. The crude oil is first heated to a relatively low temperature which vaporizes the more-volatile products. These are condensed. The boiling point of the liquid which remains in the still gradually rises as these more volatile products are driven off as vapors. At a certain temperature, the distillate is piped to

a second receiver. Here the components of the next less volatility are collected. As the boiling point reaches a certain second value, the distillate is led to a third receiver and so on until all of the "fractions" have been separated. Each of these products or fractions is still a mixture but each is composed mainly of compounds all having nearly the same boiling point. Some of the products are petroleum ether, gasoline, naphtha, benzine, kerosene, and heavier oils. At some stage, the residual oil is chilled and then crystallizes partly into flakes (either paraffin or asphalt) which, except for the filtration of paraffin, are not further treated. Certain crude oils give a paraffin residue and others an asphalt residue.

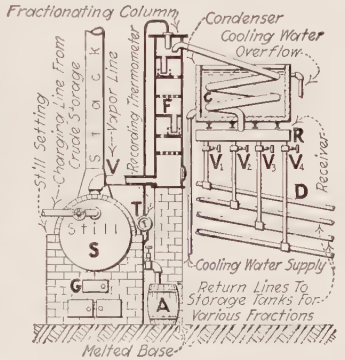

FIG. 326.—Elementary petroleum still. (Crude oil is charged into *S*, and heated by coke fire fed at *G*. The vapor rises through *V* into *F*. In this *fractionating column*, *F*, the vapors of the liquids of the higher boiling temperatures (which unavoidably are vaporized and pass over with the liquids of the lower boiling temperature) are partially condensed. The partially condensed liquids are then, in *F*, intercepted by the baffles and thereby caused to flow back into the still —instead of passing over into the condenser with the more volatile vapors. The vapors are condensed in *C* and flow into *R*. The various fractions are separated by valves, V_1, V_2, etc. according to temperature indicated by *T*. The distillate is run off through pipes *D*. The hot base—asphalt, etc.—is allowed to solidify in barrels at *A*.)

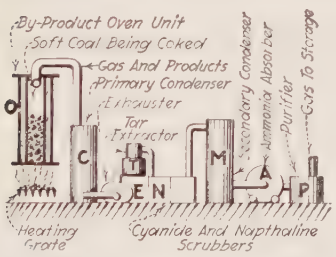

FIG. 327.—Diagram of elementary by-product coke plant. (The gas and other products given off by the coking operation in *O* are drawn, by *E*, through *C*. Tar is removed in *T* and naphthaline and cyanides in *N*. Ammonia is removed in *A* after cooling in *M* and the gas goes through *P* to storage holder.)

347. Destruction Distillation is distillation of the volatile components of solid substances, as *wood, coal, bone.* It results from a process of decomposition (Sec. 155). The substances are decomposed (Fig. 327) in closed vessels, by application of heat. The volatile ingredients are thus vaporized. The vapors resulting from different temperatures are conveyed to separate vessels wherein they are condensed. The non-volatile ingredients remain in the heating vessel as a semi-liquid or solid residuum.

348. All Gases May Be Liquefied If Subjected To Sufficiently Low Temperature And High Pressure.—If any vapor be compressed until its pressure is equal to its saturation pressure at the then existing temperature, the vapor will be condensed—that is, it will be liquefied. Again, if the temperature of a vapor be decreased until its temperature equals the saturation temperature at the then-existing pressure, the vapor will be liquefied. Or the pressure may be increased and the temperature decreased simultaneously until satura-

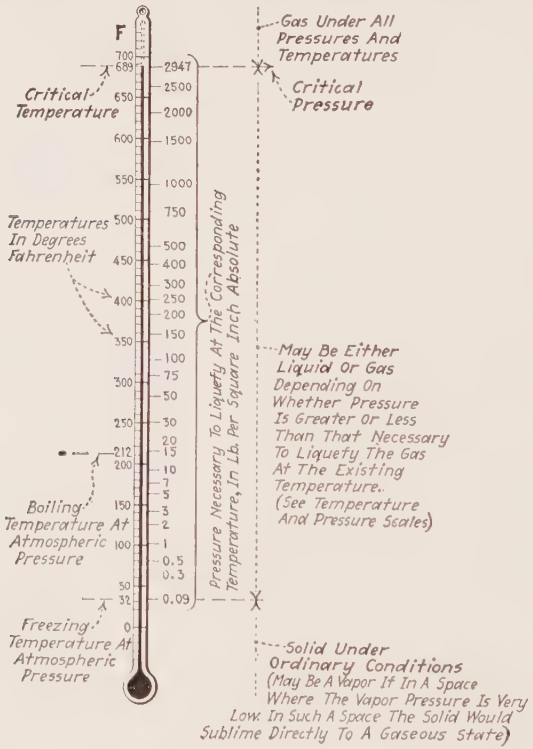

Fig. 328.—Illustrating the critical conditions for water. (According to the later steam tables, the critical temperature and pressure for water are 706.1°F. and 3,200 lb. per sq. in. abs.)

tion and consequent liquefaction occurs. There is, however, a certain temperature for every vapor, above which it cannot be liquefied (Sec. 349). Since (Sec. 225) every gas is, at certain temperatures, a vapor, these same laws hold for all gases.

Note.—A Permanent Gas was defined by Faraday as one which resisted liquefaction. Since he liquefied all known gases except hydrogen, nitrogen, oxygen, carbon monoxide and methane, these five were formerly called the permanent gases. But since then, all known gases have been liquefied. Hence, strictly speaking, there is no such thing as a permanent gas. Sometimes the term is loosely and incorrectly used to designate gases (such as the five mentioned above) which can only be liquefied at extremely low temperatures.

349. The Critical Temperature Of A Substance is that temperature above which it cannot exist as a liquid (Figs. 328 and 329). There is a certain critical temperature for each ele-

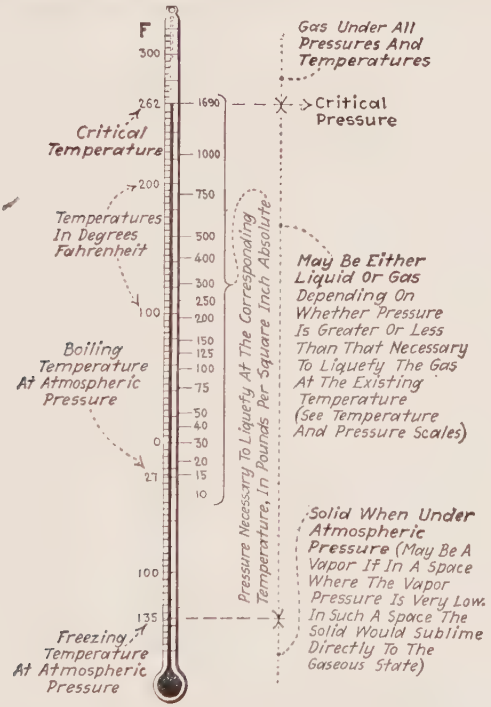

Fig. 329.—Illustrating the critical conditions for ammonia.

ment and compound; see Table 350. Above its critical temperature, no pressure (regardless of how great it is) will liquefy a substance. The pressure of a saturated vapor (Sec. 308) at its critical temperature is called its *critical pressure*. Hence, its critical pressure is the lowest pressure at which a substance

can exist in the liquid state when it is at its critical temperature. The *critical density* of a substance is its density at its critical temperature and critical pressure. The critical density of a substance is the same whether it is in the liquid or gaseous state.

Note.—The Critical Temperature Of A Substance may also be defined as that temperature above which the substance, when in its gaseous state, cannot be liquefied by pressure alone. Below its critical temperature the substance can be liquefied by pressure only.

Note.—Existence of any two of the three critical conditions: pressure, temperature, and density is contingent on the simultaneous existence of the third.

Examples.—There can be no such thing as liquid air above its critical temperature which is −220° F. (220 degrees below zero). There can be no such thing as liquid water above the critical temperature of steam which is 706° F. (Table 394).

Example.—If it is desired to change the state (Sec. 49) of gaseous air to liquid air, the first step is to subject it to a pressure of about (see Table 350) 585 lb. per sq. in. abs. Next, while the air is subjected to this pressure, it must be cooled to somewhat below its critical temperature of −220° F. Then it will be converted into liquid air. If its temperature exceeds −220° F., no pressure, however great, will liquefy it. If the temperature is less than −220° F., a pressure correspondingly less than 585 lb. per sq. in. abs. will cause liquefication.

Example.—Consider a quantity of water which is confined in a closed vessel. The vessel is heated. Thereby some of the water is vaporized. As additional heat is imparted and more of the water vaporized, the pressure within the vessel increases. This increases the density of the vapor. But as the temperature rises, the density of the water diminishes (Sec. 205). Ultimately a temperature and pressure will be reached at which the density of the steam will be equal to that of the water. This temperature and pressure are, approximately, 706° F. and 3,200 lb. per sq. in. abs. (Marks and Davis' Steam Tables). When this condition has developed, any further addition of heat will change all the water into steam since the water has then no latent heat of vaporization. A slight loss in heat will then result in instantaneous condensation of a considerable quantity of water.

Example.—If approximately equal volumes of liquid carbon dioxide and its saturated vapor are sealed (Fig. 330) in a heavy-walled glass tube, it may be easily heated above the critical temperature of carbon dioxide (88° F.) in warm water. As the temperature of the water approaches 88° F., the meniscus, *A*, or dividing line between the liquid and the vapor will give way to a foggy appearance at the point, *B*. At the instant that the critical temperature is passed, the tube will be full of gas only and will appear to be empty.

Note.—The Ease With Which The Critical Temperature Of A Gas May Be Attained Largely Determines The Facility With Which The Gas May Be Liquefied.—The vapors of many substances such as: water, alcohol, ether, ammonia, and carbon dioxide may be

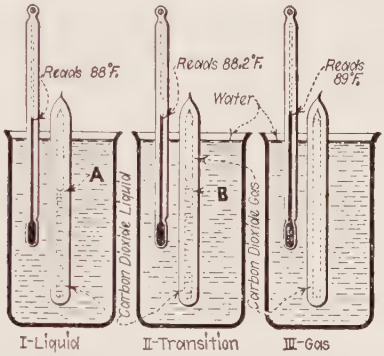

Fig. 330.—Showing vaporization of carbon dioxide at critical temperature and pressure.

readily liquefied since temperatures (Table 350) well below their critical temperatures can readily be obtained. But liquefaction of certain gaseous substances such as air, carbon monoxide, and hydrogen is accomplished only with considerable difficulty. The reason is that the critical temperatures of these gases are (Table 350) extremely low and therefore difficult to obtain.

350. Table Showing Critical Temperatures and Pressures Of Various Substances. (From Marks' MECHANICAL ENGINEERS' HANDBOOK.)

Substance	Critical temperature, deg. Fahr.	Critical pressure		Boiling temperature of liquid at atmospheric pressure, deg. Fahr.
		[1] In atmospheres	In lb. per sq. in.	
Acetylene (C_2H_2)	95.0	68.0	1,000	−117.4
Air	−220.0	39.0	573	
Alcohol (C_2H_6O)	421.0	65.0	956	172.4
Ammonia (NH_3)	266.0	115.0	1,691	− 27.4
Benzol (C_6H_6)	554.0	50.0	735	176.0
Bromine	512.0	....	.....	142.0
Carbon dioxide	88.2	77.0	1,132	−110.0
Carbon monoxide	−222.0	35.9	528	−310.0
Carbon disulphide	468.0	78.1	1,148	115.0
Chloroform	500.0	54.9	807	141.0
Chlorine	289.0	92.0	1,352	− 27.4
Ether ($C_4H_{10}O$)	381.2	37.0	544	95.0
Ethane	31.0	45.2	665	−135.0
Ethylene	50.0	54.0	794	−157.0
Helium	−448.6	3.0	44.1	−450.4
Hydrogen	−402.0	20.0	294	−423.0
Hydrogen chloride	125.6	87.0	1,278	−112.0
Hydrogen sulphide	212.0	94.0	1,382	− 61.6
Methane (CH_4)	−115.6	57.0	838	−263.0
Nitric oxide (NO)	−137.2	73.0	1,073	−238.0
Nitrous oxide (N_2O)	96.8	80.0	1,175	−134.0
Nitrogen	−236.0	35.0	514	−321.0
Oxygen	−180.4	50.0	735	−297.0
Pentane	386.6	34.0	500	96.8
Sulphur dioxide	314.6	80.0	1,175	14.0
[2] Water	706.1	217.8	3,200	212.0

[1] 1 atmosphere = 14.7 lb. per sq. in.

From Marks and Davis' STEAM TABLES.

QUESTIONS ON DIVISION 10

1. Define *vaporization*. Give some examples of its practical applications.

2. Explain in general terms the distinction between a gas and a vapor.

3. What kind of a vapor is steam?

4. Name and define the three different kinds of vaporization.

5. Under what temperature conditions will evaporation occur?

6. Explain the molecular theory of evaporation.

7. State the laws governing evaporation. Explain each law.

8. What effect does evaporation have on the temperature of the evaporating liquid and the adjacent bodies? Explain. Give two commercial applications.

9. Give some examples of freezing and cooling by evaporation.

10. What is condensation? Explain. Give a practical application of heating by condensation.

11. What change in volume takes place when a substance vaporizes or condenses?

12. What is a saturated vapor? Explain saturation theoretically. What happens if a saturated vapor is cooled at a given pressure?

13. What are Dalton's laws for vapors? Explain an exception to the second law.

14. What determines the vapor pressure of a given liquid? What effect has the presence of another gas on evaporation? On vapor pressure?

15. What is meant by saturation pressure?

16. Why do bubbles form when a liquid is heated to its boiling point? Of what are they composed? Why do they sometimes disappear before they reach the liquid surface.

17. Why is ebullition usually more rapid than evaporation?

18. What is the relation between vapor pressure and boiling point? Illustrate with a sketch showing the forces which act upon a bubble.

19. Why does not a body of liquid all evaporate at once when heat is applied to it at its boiling point?

20. How does difference in pressure affect boiling point? Describe an experiment in which boiling point is lowered by a pressure change. One in which it is raised.

21. How is the boiling point of a liquid affected by a dissolved solid? By a dissolved gas?

22. Give two examples of sublimation.

23. What is latent heat of vaporization? Into what two parts may it be divided? Explain.

24. Why is the large latent heat of vaporization of water a disadvantage in steam power generation? An advantage in steam heating?

25. How does increased pressure and temperature affect latent heat of vaporization?

26. What are the principal constituents of atmospheric air?

27. Define *humidity*. In what two ways may the atmospheric humidity be expressed numerically?

28. What degree of humidity is most suitable for animal life? How may the humidity be increased artificially? How decreased?

29. Explain the principle and use of the psychrometer in determining relative humidity. What is the practical use of such determinations?

30. What is meant by *dew point*? How is dew formed?

31. Explain the *sweating* of cold objects in warm air. How may it be prevented? Give 2 ways.

32. Explain frost, fog, and rain? How is snow formed?

33. Explain fractional distillation. Destructive distillation. Give a commercial application of each.

34. What is the critical temperature of a substance? What is its critical pressure? Critical density? Describe condensation and vaporization at critical temperature and pressure

35. What is the effect of the critical temperature of a gas on the ease with which it can be liquefied?

PROBLEMS ON DIVISION 10

1. How much heat must be added to 1 lb. of water at 32° F. to change it to steam at atmospheric pressure?

2. How much heat must be added to 1 lb. of ice at 32° F. to change it to steam at atmospheric pressure?

3. What is the weight of the water vapor in 1 cu. ft. of air at a temperature of 70° F., if the relative humidity is 55 per cent.?

4. The temperature of the wet- and dry-bulb thermometers in a room are 70° F. and 53° F. respectively. What is the relative humidity and what weight of water vapor does each cubic foot of air contain? Compute from the tables.

5. In an industrial plant, the wet- and dry-bulb temperatures are respectively 90° F. and 75° F. on a summer day. Find, by means of the psychrometric chart of Fig. 323, the relative humidity and the weight of water vapor in 1 cu. ft. of the air.

6. If, in the plant of Prob. 5, a relative humidity of 80 per cent. is necessary for certain processes, find what the wet-bulb thermometer should be made to read and how much moisture must be added to each cubic foot of air.

7. If, in Prob. 6, it is desired to raise the relative humidity by cooling the air, to what temperature must it be cooled?

8. (*a*) What is the state of water at the temperature of 800° F. and under the pressure of 200 lb. per sq. in. abs.? (*b*) At 800° F. and 3,500 lb. per sq. in abs.? (*c*) At 1,000 lb. per. sq. in. abs. and 500° F.? (*d*) At 350° F. and 75 lb. per sq. in. abs.?

9. (*a*) What is the state of ammonia at 70° F. and 100 lb. per sq. in. abs.? (*b*) At 700° F. and 500 lb. per sq. in. abs.? (*c*) At 140° F. and 500 lb. per sq. in. abs.? (*d*) At 0° F. and atmospheric pressure?

DIVISION 11

STEAM AND OTHER VAPORS

351. A Vapor Is Any Substance In The Gaseous State Which Does Not Even Approximately Follow The General Gas Law (Figs. 331 and 332). That is, as explained in Sec. 225, vapors are substances in the gaseous state at or near their liquefaction conditions. The general gas law is explained in Sec. 248. The reason for this departure of the performance of vapors from the general gas law is that the vapors, when heated or cooled, experience some disgregation work (Sec. 98). The general gas law is based on a perfect gas which would experience no disgregation work when heated or cooled (Sec. 258). But all known actual gases do experience small amounts of disgregation work. Vapors experience large amounts of disgregation work; this is very evident at the boiling point of a liquid at which point the liquid is changed to a vapor and a great change of volume occurs with no change in the

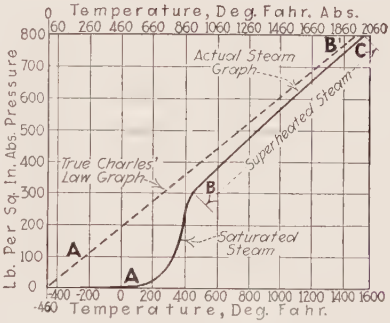

FIG. 331.—Showing deviation, of relation of temperature to pressure of steam, from Charles' law. Graph *ABC* shows the actual behavior of—water vapor—steam. (The values are for 1 lb. of steam confined to a constant volume of 1.62 cu. ft. If steam were a perfect gas, the graph would take the form of the dotted line *A' B'*.)

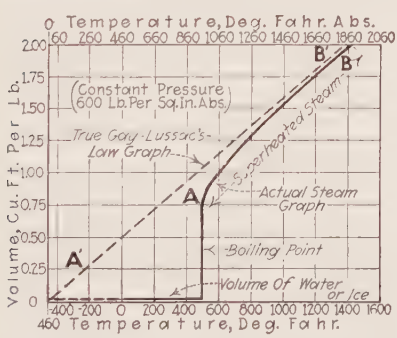

FIG. 332.—Showing deviation of water vapor —steam—from Gay Lussac's law at 600 lb. per sq. in. abs. pressure.

pressure which is exerted by the vapor or in its temperature. The consequence is that, for most vapor calculations, it is infeasible to use formulas. Instead, it is necessary to use values which have been determined by experiment and listed in tables. The use of these tables will be described later; the Steam Table 394 is an example.

Note.—Highly Superheated Vapors Are Gases, if the superheat is sufficiently great, and they do then approximately follow the perfect gas laws.

352. Vapors Are Essential To The Operation Of Most Refrigerating Plants, Many Power Plants And For Many Industrial Processes.—Hence, a knowledge of their properties and behavior is very important to the engineer. Water vapor —steam—is used to generate more power than any other substance; see following Sec. 391. The vapors, ammonia, sulphur dioxide, and carbon dioxide are practically the only substances used as refrigerants in the manufacture of artificial ice; see Div. 18. The examples just stated indicate how extensively vapors are used in industry. All behave similarly even though they have different boiling points. Thus, the general principles stated in this division are true for all vapors. But the properties of only the four important vapors, named above, will be treated in detail.

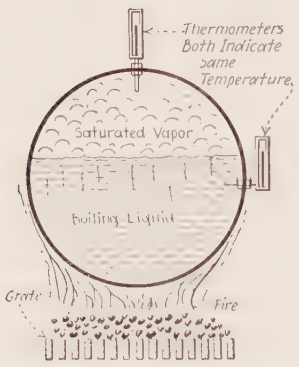

Fig. 333.—Illustrating the meaning of the term "saturated vapor"

353. Vapors May Occur In Any One Of Three Conditions: (1) *Saturated vapor* which may be either wet or dry. (2) *Superheated vapor.* (3) *Supersaturated vapor.* Each of these conditions will be discussed separately.

354. Saturated Vapor Fig. 333 (see also discussion and definition given in Sec. 305), is vapor at the temperature corresponding to the boiling point of the liquid at the imposed pressure. As explained in Sec. 315, there is, for each different liquid substance, a certain definite boiling point for each pressure. A

substance which is in the vaporous form in a confined space and which is in contact with some of the same substance which is in the liquid state, is always at the same temperature as the liquid and is saturated vapor. When heat is added to a confined (at constant pressure) body of saturated vapor and to the liquid with which it is in contact, more of the liquid vaporizes but the temperature of the liquid and vapor remains constant. Similarly if heat is extracted, more of the vapor will condense but the temperature will also remain constant. The temperature will not change until the liquid is all vaporized or until the vapor is all condensed; see Sec. 322 on "latent heat of vaporization." If the pressure to which the saturated vapor and its liquid are subjected is varied, the temperature of both liquid and vapor will always vary correspondingly with it—but the temperature of the confined vapor will in every case be the same as that of the liquid.

Note.—For A Given Pressure, The Temperature And Density Of A Saturated Vapor Are Fixed.—The temperature and density cannot be changed without also changing the pressure; see Sec. 305; also see Steam Table 394.

355. Saturated Vapors May Be Either Dry Or Wet.—*A dry saturated vapor* is one that does not contain any liquid. It contains just sufficient heat energy to maintain all of the substance in the vaporous form; see also Sec. 305. *A wet vapor* is one that is saturated but it also contains liquid particles, (Fig. 334), either in the form of mist or as fine droplets in suspension. It does not contain sufficient heat energy to maintain all of the substance in the vaporous state.

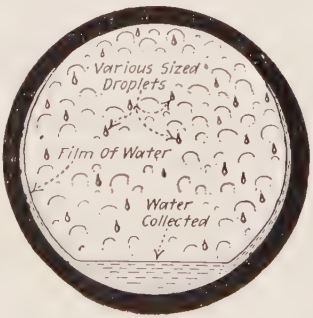

Fig. 334.—Cross-section of steam pipe showing the distribution of water in a main carrying wet steam.

Note.—If Some Of The Heat Of Dry Saturated Vapor Is Absorbed by an outside body, some of the vapor will condense and wet vapor will result.

Note.—In Practice Where The Vapor Is Produced By Boiling, It Is Difficult To Obtain An Absolutely Dry Saturated Vapor,

because, if boiling takes place at even a moderate rate, some liquid particles are always carried upward with the rising vapor. Furthermore, when the vapor is transmitted any considerable distance through pipes, it usually loses some heat which causes more vapor to condense (Sec. 301) and consequently produces more liquid in the vapor.

356. Superheated Vapor is vapor the temperature of which is greater than that of the boiling point corresponding to the pressure imposed on it. The temperature of a vapor may be increased above that corresponding to the imposed pressure by adding heat to the vapor (Fig. 335) after the liquid has all

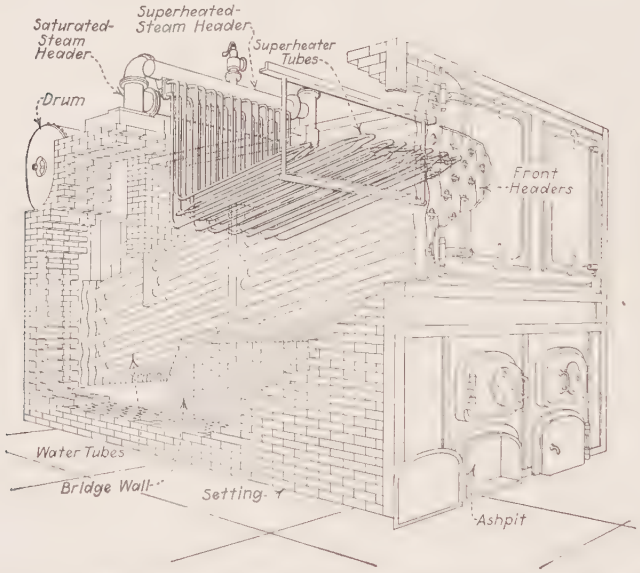

Fig. 335.—"Elesco" superheater applied to a water-tube boiler of the cross-drum type. (*The Superheater Company.*)

been vaporized or after the vapor has been separated from contact with the liquid. Superheated vapor contains more heat energy than that required merely to maintain the substance in the vaporous condition. It contains the additional heat energy required to raise the temperature of the vapor above the temperature corresponding to the pressure. The superheated condition of a vapor in one which is not in thermal equilibrium with the liquid, for if superheated vapor is brought

in contact with the liquid substance, it will give up that portion of its additional heat which is required to vaporize the liquid, providing it contains that much additional heat. If it does not contain sufficient additional heat to vaporize all the liquid, it will give up all its additional heat and some of the liquid will not be vaporized.

Note.—While Saturated Vapor Can Have Only One Temperature And Density For A Given Pressure, Superheated Vapor Can Have Any Temperature Above The Boiling Point And Any Density less than that of saturated vapor, for the given pressure. At constant pressure the temperature of superheated vapor increases with the heat added.

Note.—The Amount Of Superheat In A Vapor Is Given in terms of the difference between its temperature and that of saturated vapor at the same pressure. Thus, vapor which has a temperature 50° higher than saturated vapor at the same pressure is said to contain "50° of superheat."

357. Supersaturated Vapor is vapor the temperature of which is less and the density of which is greater than that corresponding to the pressure imposed on it. This condition is obtained when vapor is cooled by its own expansion until it contains less heat energy than would the saturated vapor under the same conditions. This condition cannot always be obtained because—after the heat energy of the vapor is reduced to that of saturated vapor under the same conditions, and then more heat is abstracted—some of the vapor usually condenses and the heat in the remaining vapor is the same. Under certain special conditions, however, for some reason not fully understood, condensation does not take place and the vapor changes to the supersaturated condition. This condition is a very unstable one and the vapor soon resumes the saturated condition.

Note.—This Supersaturated Condition Of Vapor Is Ordinarily Of No Importance In Power Plant Practice except to the turbine designer—it occurs only in the expansion in a turbine or other nozzle. It is mentioned here only to show that this condition may exist. It will not be further discussed.

358. Vapors, When Used In Engineering Processes, Do Not Remain In The Same Condition Throughout The Process; That Is, Their "Properties" Change.—At certain points in a

process the substance may be all vapor, at other points it may be all liquid, while at intermediate points it may be part liquid and part vapor. The pressure on the vapor may vary through a wide range and also the temperature. With these pressure and temperature changes, the volume of 1 lb. of the substance must also change. The fact that the working substance is used as a vehicle for conveying heat, necessitates its possessing a different quantity of heat at different points or conditions. These several qualities, *pressure, temperature, specific volume, heat content,* and others which are related to one another are spoken of as the *properties of the vapor.*

359. The Various Properties Of Each Vapor Are Interrelated. That is, they depend upon one another; hence, if some of them are given or observed, the others may be found. It was shown in preceding Sec. 354, that for saturated vapor at a given pressure, the temperature is always the same. Thus, if the pressure of saturated vapor is observed, its temperature can be found from a vapor table in which the results of previous experiments are tabulated. Likewise, all the other properties of a given weight of a certain vapor which will be described later, such as latent heat of vaporization, can be found when any two properties, such as the pressure and quality for saturated vapor or the pressure and temperature for superheated vapor, are known. However, if it is known that the vapor is dry and saturated only one other property such as the pressure need be known, since the knowledge that it is dry constitutes the second known property which is "quality."

Note.—For Dry Saturated Vapor, The Pressure Need Not Be The Observed Property.—Any property may be the observed one and all the other properties may be found from it. In steam practice the pressure is usually observed while in refrigeration practice the temperature is observed. Likewise with wet saturated or superheated vapor any two properties may be observed to determine the remainder. But for wet saturated vapor, temperature and pressure cannot be counted as two properties for one determines the other; hence, another property besides either one of them must be given.

Note.—Pressure Gages, Thermometers, And Vapor Calorimeters are used to determine the properties of the substances at various points. Vapor calorimeters (Sec. 392) determine the percentage of liquid carried with the vapor.

360. By The "Quality" Of Saturated Vapor is meant the percentage of dry vapor present in the given amount of the wet saturated vapor. It is, in this book, usually expressed as a decimal but it is often expressed as a percentage. That is, if 100 lb. of wet vapor contains 2 lb. of liquid and 98 lb. of dry vapor, the quality of the vapor is 98 per cent. or 0.98. It is important to know the quality of a vapor in ascertaining its heat content per pound (see Sec. 365). "Quality" is also used in calculating engine economies. Quality is determined by means of vapor or steam calorimeters, as is explained in Sec. 392.

Example.—Assume that an engine requires 10,000 lb. of dry steam per hour for a given output. It is found that the quality of the steam furnished to it is 94 per cent. Neglecting the heat of liquid in the water, what weight of wet steam must be furnished? Solution.—The 10,000 lb. of steam is 94 per cent. of the weight of wet steam necessary. Then: *the weight of wet steam required* = 10,000 ÷ 0.94 = 10,630 *lb. per hr.*

361. The Properties Of The Vapors Used In Practice Are Arranged In "Vapor Tables."—The values found therein (Tables 394, 395, 399, 400 and 401) have been determined accurately by experiment. They form the basis for many vapor calculations. Such tables must be employed because the properties of vapors cannot be determined from the general gas law (Sec. 248) or other simple formulas. *The values given in the tables are for dry saturated vapors* but they may be used also for wet-vapor computations. When they are so used, the amount of liquid present in the wet vapor must be given consideration. This is necessary because the tables give values which apply only to the vapor and not to the liquid and vapor together; see Sec. 366. The tables given in this division are abstracts of more extensive tables; but they are complete enough for most engineering work except engine, turbine, or refrigeration-compressor designing.

Note.—The Heat-content Values Shown In The Vapor Tables Indicate Only The Heats Of 1 Lb. The Vapor Above 32° F. Liquid, although the liquid at 32° F. does contain some heat. As explained in Sec. 108, some starting point must be chosen because the total heat in a body, that above 0° F. abs., cannot be measured. This arbitrarily chosen point, the liquid state at 32° F., is a convenient one for most vapors. Calculations will not be affected by the temperature which is

thus used as this starting point (or datum) above which the total heat of the vapor is considered, for in engineering only the *difference* in heat content between two conditions of the vapor is desired and *not the total heats*. Almost any reasonable temperature other than 32° F. might have been chosen as the standard starting point; but 32° F. *was* chosen. It is convenient and hence is widely used.

Note.—There Are Two Tables For Each Vapor.—One table contains the properties of the dry saturated vapor and the other the properties of the superheated vapor. The table of the properties of superheated steam is the only table of superheated vapors given in this volume. The properties of wet vapor can be determined from the table of dry saturated-vapor properties by the method shown in Sec. 366. The properties of supersaturated vapors are not tabulated since this condition of vapor, as stated in Sec. 357, seldom occurs in engineering practice.

362. To Determine The Properties Of A Vapor At Some Pressure Between Those Given In Tables 394, 395, 399, and 400, *interpolate* as explained below and by the following example. This method is quite accurate. There are, however, charts of the properties of vapors, as shown in Fig. 343, from which these intermediate values can be read directly. If the charts are large and accurately made, the values obtained from them will be more accurate than those found by interpolation of the values given in the table. However, most charts are small and not precisely printed, which tends to render them inaccurate. Hence charts should not be used for exact computations unless they have been previously checked with a table of known accuracy. Charts will be further discussed in Sec. 382.

Example.—Find the temperature and latent heat of 1 lb. of steam at 154 lb. per sq. in. abs. Solution.—The pressure, 154 lb. per sq. in. abs., is 0.4 of the range from 150 to 160 in Column 2, Table 394. That is, $160 - 150 = 10$ and $154 - 150 = 4$, and $4 \div 10 = 0.4$. Therefore, the temperature at this pressure is approximately 0.4 of the range from 358.5 to 363.6° F., greater than 358.5° F. Thus it will be: $358.5 + 0.4(363.6 - 358.5) = 360.5$° F. Similarly, the latent heat of steam at 154 lb. per sq. in. abs. is: $863.2 - 0.4(863.2 - 858.8) = 861.5$ *B.t.u.*

363. The Heat Of The Liquid, h (Tables 394, 399, 400 and 401), as given in tables of vapor properties, is the heat in British thermal units required to raise the temperature of 1 lb. of the liquid from 32° F. to that temperature at which the liquid begins to boil at the given pressure, P. In changing a

liquid to a vapor under constant pressure, the temperature of the liquid must first be brought up to its boiling point at the given pressure before the liquid can evaporate (Sec. 315). The heat required to do this is called the heat of the liquid.

Note.—The Heat Of The Liquid May Be Found Approximately By Multiplying The Specific Heat Of The Liquid By The Temperature Rise; see Sec. 92. For water the specific heat is approximately 1. Hence the heat of the liquid for water vapor or steam then must be approximately equal to the difference in temperature between the temperature under consideration and 32° F. See Table 394, column 5.

Example.—The heat of 1 lb. of liquid (water) at 261° F., as shown by Steam Table 394, is 229.6 B.t.u. *The temperature difference between* 261 *and* 32° *F.* = 261 − 32 = 229° *F.* This value is nearly equal to the actual heat of liquid in B.t.u.—229.6—as shown by the steam table. The correct value is the one given in the steam table.

Note.—The Heat Of The Liquid Increases With The Pressure.—Since the temperature increases with the pressure, the heat of the liquid must also increase with the pressure.

Note.—Vapors Are Often Used Below 32° F. In Refrigeration Processes (see Tables 399, 400, and 401). For temperatures below 32° F., the heat of the liquid given in the table must be extracted from, instead of added to the liquid at 32° F. to bring it to the temperature under consideration. Hence, the heat of the liquid is given the negative sign in the vapor tables when the temperature of the liquid is below 32° F. At 32° F. the heat of the liquid must be zero.

364. The Latent Heat Of Vaporization, L, (see Sec. 322 for definition) is also given in the vapor tables. The value of the latent heat of vaporization decreases as the imposed pressure increases (see Tables 394, 399, 400, and 491 for saturated vapors) until the critical pressure is reached; there it becomes zero. The latent heat of vaporization is, as explained in Sec. 325, divided into two parts: (1) *The external latent heat of vaporization*—external-work heat—which is equivalent to the amount of mechanical work done by the vapor in expanding from the liquid to the vapor state. (2) *The internal latent heat of vaporization*—disgregation heat—which is the increase in internal heat energy accompanying the vaporization; see also Sec. 107. The values for these two parts of the latent heat of vaporization are also given in the saturated-vapor tables in the columns headed L_E and L_I respectively. It is a useful fact to remember that it requires about 1,000 B.t.u. (see Steam Table 394) to vaporize 1 lb. of water at atmospheric pressure.

Note.—No Value For The Latent Heat Of Vaporization Is Given In Table 395 Of The Properties Of Superheated Water Vapor. —These values can be found from the table of the properties of saturated vapors under the latent heats of vaporization for the same pressure; see following example. The latent heat depends on the pressure and not on the amount of superheat.

Note.—The Terms "Latent Heat Of The Vapor" and "Heat Of Vaporization" are sometimes used instead of "Latent Heat of Vaporization."

Example.—Find the amount of heat that was required to vaporize 10 lb. of steam which is at 160 lb. per sq. in. gage and has a temperature of 500° F. Solution.—From saturated-steam Table 394, the temperature of steam which is at 160 lb. per sq. in. gage pressure, is found to be only 370.8° F. Hence the steam given in this example must be superheated steam. But this does not affect the solution of the problem because the heat of vaporization of superheated steam is the same as that for saturated steam at same pressure. In saturated-steam Table 394 on the horizontal line with 160 lb. per sq. in. gage pressure in the **L** (heat-of-vaporization) column is the value "852.7." This is the heat in B.t.u. required to vaporize 1 lb. of steam. To vaporize 10 lb. of steam: $10 \times 852.7 = 8{,}527$ *B.t.u.* are required.

365. The Total Heat Of A Vapor, ($\mathbf{H}_D$ Column 4, Table 394), is the amount of heat which must be supplied to 1 lb. of the liquid which is at 32° F, to convert it, at constant pressure, into vapor at the temperature and pressure considered. This value is given in both the tables of the properties of saturated vapors and those of the properties of superheated vapors. The total heat is, for dry saturated vapor, the sum of the heat of the liquid, **h**, and the latent heat of vaporization, **L**; see Sec. 108. The total heat of any dry saturated vapor increases with the pressure. For superheated vapors, the total heat (Table 395) includes not only the heat of the liquid and the latent heat of vaporization but also the additional heat required to superheat the vapor.

Note.—The Total Heat Of A Vapor Depends On How The Vapor Is Heated.—The total heat given in the tables is for heating at constant pressure. If the liquid is heated in some other manner, as at constant volume, the total heat added would be different.

Example.—Find the amount of heat which must be supplied to 53 lb. of water at 59° F. to convert it into saturated steam at 250.3° F. Do not use the $\mathbf{H}_D$ values in Column 4 of Table 394.

Solution.—The heat of liquid at 250.3° F. is 218.8 B.t.u. per lb. At 59° F. it is 27.08 B.t.u. per lb. The amount of heat that must be added

to the liquid to raise it to the required temperature is then: 218.8 − 27.08 = 191.72 *B.t.u. per lb.* The heat required to vaporize the liquid at 250.3° F. is 945.1 B.t.u. per lb. Hence, the total heat required is: (945.1 + 191.72) × 53 = 1,136.82 × 53 = 60,250 *B.t.u.* for 53 lb. Note. —This result would be obtained in practice by subtracting the heat of liquid, 27.08 B.t.u., from the total heat of steam 1,163.9 giving 1,136.82 B.t.u. per lb. as before.

366. The Total Heat Of A Wet Saturated Vapor Cannot Be Obtained Directly From The Vapor Tables.—However, it can be calculated when the quality is known by the use of the following formula, the derivation of which is given below:

(242) $$H_W = h + xL$$ (B.t.u. per pound)

Wherein: H_W = the total heat of wet vapor, in British thermal units per pound. h = the heat of liquid at the temperature of the wet vapor, in British thermal units per pound. x = the quality of the wet vapor, expressed decimally; that is, the fraction of the mixture that is vaporized. L = the latent heat of dry saturated vapor at the pressure of the wet vapor.

Example.—Find the total heat of 1,100 lb. of wet ammonia vapor having a quality of 96 per cent. The temperature of the vapor is 60° F.

Solution.—From Table 400 for the vapor at 60° F., h = 30.9 *B.t.u. per lb.* and L = 522 *B.t.u. per lb.* By For. (242): the total heat per lb., $H_W = h + xL = 30.9 + (0.96 \times 522) = 30.9 + 501.1 = 532$ *B.t.u. per lb.* For 1,100 lb.: *the total heat* = 1,100 × 532 = 585,200 *B.t.u.*

Derivation.—Wet vapor (Sec. 355) has liquid particles suspended in it. Since the liquid particles contained in the wet vapor are at the same temperature as the vapor, the heat of the liquid, h, contained in a given weight of wet vapor must be the same as that contained in the same weight of dry saturated vapor at the same pressure. But also, the vapor portion of wet vapor contains latent heat of vaporization. Now, by definition, the weight of dry vapor in 1 lb. of wet vapor is equal to the quality, x, of the vapor expressed decimally. Hence, the latent heat in 1 lb. of wet vapor must equal the latent heat, L, of dry saturated vapor times the quality. That is, *the latent heat present in 1 lb. of wet vapor* = xL. Hence the total heat present is:

(243) $$H_W = h + xL$$ (B.t.u. per lb.)

which is the same as For. (242).

367. The Total Heat Of Superheated Vapor Can Be Computed When No Table Of Superheated-vapor Properties Is At Hand.—The temperature and pressure of the vapor must both be known. For steam, find the temperature in Steam

Table 394 corresponding to the pressure of the vapor. The difference between this temperature and the observed temperature is (Sec. 356) called the *degrees of superheat.* Then find, from the graph of Fig. 336, the mean specific heat of superheated steam for this pressure and degree of superheat. Now, the total heat of superheated vapor is:

(244) $$\mathbf{H}_S = \mathbf{H}_D + \mathbf{C}T_S \qquad \text{(B.t.u. per lb.)}$$

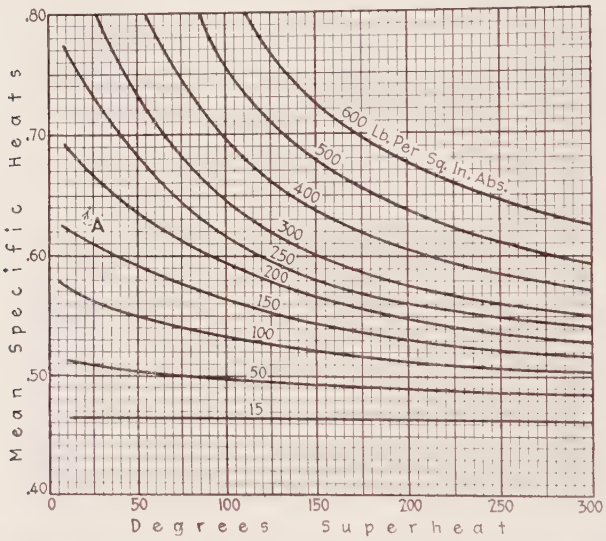

Fig. 336.—Chart showing mean specific heat of superheated steam for various pressures and degrees of superheat.

Wherein: $\mathbf{H}_S$ = the total heat of superheated vapor, in British thermal units per pound. $\mathbf{H}_D$ = the total heat of saturated vapor at the same pressure as that of the superheated vapor, in British thermal units per pound. $\mathbf{C}$ = the mean specific heat of superheated vapor at the pressure and degrees of superheat considered; for steam see Fig. 336; for other vapors see note below; T_S = the degrees of superheat of the vapor, in degrees Fahrenheit.

Example.—A certain volume of steam has a temperature of 397° F. and a pressure of 180 lb. per sq. in. abs., what is the total heat per pound? Solution.—The temperature corresponding in Steam Table 394, to

180 lb. per sq. in. abs. is 373.1° F. There are, therefore: 397 − 373.1 = 23.9° F. *of superheat.* The mean specific heat of superheated steam under these conditions is (*A*, Fig. 336) 0.64. Hence, by For. (244), the total heat of superheated steam: $\mathbf{H}_S = \mathbf{H}_D + \mathbf{C}T_S = 1{,}196.4 + (0.64 \times 23.9) = 1{,}211.3$ *B.t.u. per lb.*

Note.—The Mean Specific Heats Of Superheated Ammonia, Carbon Dioxide, And Sulphur Dioxide, throughout the ordinary working ranges, may be taken as: ammonia, 0.52; carbon dioxide, 0.21; sulphur dioxide, 0.15. These are specific heats at constant pressure, Sec. 267.

368. The Specific Volumes Of Vapors (the volumes of 1 lb.) are given in the vapor tables for dry saturated vapors and for superheated steam. The specific volumes of superheated ammonia, carbon dioxide, and sulphur dioxide may be found with reasonable accuracy by applying the general gas law and the constants given in Div. 8. The specific volumes of wet vapors may be computed, with reasonable accuracy, by For. (245) below. If extreme accuracy is desired For. (246) may be used.

(245) $$V_W = \mathbf{x}V_D \qquad \text{(cu. ft. per lb.)}$$

Wherein: V_W = the specific volume of the wet vapor, in cubic feet per pound. $\mathbf{x}$ = the quality of the vapor, expressed decimally. V_D = the specific volume of dry saturated vapor of the same pressure, in cubic feet per pound; V_D can be found from the vapor tables.

Derivation.—Since 1 lb. of the wet vapor contains $\mathbf{x}$ lb. of dry saturated vapor and $(1 - \mathbf{x})$ lb. of liquid at the boiling temperature, the specific volume of the wet vapor must be the sum of the volumes occupied by $\mathbf{x}$ lb. of dry saturated vapor and $(1 - \mathbf{x})$ lb. of liquid. If V_L is the specific volume of the liquid at the boiling temperature, then the volume of $(1 - \mathbf{x})$ lb. of liquid will be $(1 - \mathbf{x}) \times V_L$ cu. ft. Also, the volume of $\mathbf{x}$ lb. of dry saturated vapor will be $\mathbf{x} \times V_D$ cu. ft. Hence, the specific volume of the wet vapor,

(246) $$V_W = (1 - \mathbf{x})V_L + \mathbf{x}V_D \qquad \textit{(cu. ft.)}$$

But, the specific volume of the liquid is ordinarily very small as compared with that of the dry saturated vapor. Hence, except for very wet vapor ($\mathbf{x}$ very small), only a negligible error is introduced by disregarding the term of For. (246) which expresses the volume of the liquid. When this term is disregarded, For. (245) results.

Example.—What is the specific volume of steam of 80 per cent. quality at 125 lb. per sq. in. abs.? Solution.—From steam Table 394,

at 125 lb. per sq. in. abs., $V_D = 3.583$ cu. ft. per lb. Hence, by For. (245), the *specific volume of the wet steam* $= V_W = \mathbf{x}V_D = 0.80 \times 3.583 = 2.866$ *cu. ft. per lb.*

Note.—To Find The Quality Of Wet Steam When Its Specific Volume And Its Pressure Or Temperature Are Known, the following formula—a transposed form of For. (245)—may be used

$$\mathbf{x} = \frac{V_W}{V_D} \qquad \text{(decimal)} \tag{247}$$

Example.—If 2 lb. of steam at 281° F. are contained in an engine cylinder whose volume is 12 cu. ft., what is the quality of the steam? Solution.—The *specific volume* $= V_W = 12 \div 2 = 6$ *cu. ft. per lb.* At 281° F., by Table 394, the specific volume of dry saturated steam is 8.51 cu. ft. per lb. Hence, the steam in the cylinder is *wet.* Then, by For. (247), the *quality* $= \mathbf{x} = V_W/V_D = 6 \div 8.51 = 0.705$ or 70.5 *per cent.*

369. The "Internal Heat" or "Internal Energy" Of A Vapor (see Sec. 107, for definition) can readily be computed. As explained in Sec. 103, nearly all of the heat of the liquid (**h** in the vapor tables) represents vibration heat and is therefore internal heat. Likewise, during vaporization, a great portion of the latent heat of vaporization is stored as internal energy (in Table 394 the latent heat is divided into internal and external heats). For any liquid, vapor, or mixture of liquid and vapor, the internal energy per pound (measured above that of the liquid at 32° F.) may be found from the tables by the formula:

$$\mathbf{I} = \mathbf{H} - 0.185{,}2PV \qquad \text{(B.t.u. per lb.)} \tag{248}$$

Wherein: **I** = the internal energy of the liquid or vapor, in British thermal units per pound. **H** = the heat content (Sec. 365) of the liquid or vapor, in British thermal units per pound. P = the pressure of the vapor, or the pressure at which the liquid will boil at its temperature, in pounds per square inch absolute. V = the specific volume of the liquid or vapor, in cubic feet per pound.

Derivation.—Formula (248) is the direct result of transposition and simplification of the formula which is used by the compilers of the vapor tables as the definition of heat content, namely:

$$\mathbf{H} = \mathbf{I} + \frac{144PV}{778} \tag{249}$$

Example.—What is the internal energy of 1 lb. of dry saturated water vapor at 366° F.? Solution.—By Table 394, for the given condi-

tion: $\mathbf{H} = 1{,}195.0$ B.t.u. per lb.; $P = 165$ lb. per sq. in. abs.; $V = 2.753$ cu. ft. per lb. Hence, by For. (248), the *internal energy* $= \mathbf{I} = \mathbf{H} - 0.185{,}2PV = 1{,}195.0 - (0.185{,}2 \times 165 \times 2.753) = 1{,}110.8$ *B.t.u. per lb.*

EXAMPLE.—What is the internal energy of 1 lb. of steam at 200 lb. per sq. in. abs. and superheated by 150° F.? SOLUTION.—By Table 395, for the given conditions, $\mathbf{H} = 1{,}282.6$ B.t.u. per lb., and $V = 2.86$ cu. ft. per lb. Hence, by For. (248), the *internal energy* $= \mathbf{I} = \mathbf{H} - 0.185{,}2PV = 1{,}282.6 - (0.185{,}2 \times 200 \times 2.86) = 1{,}176.6$ *B.t.u. per lb.*

EXAMPLE.—What is the internal energy of 1 lb. of steam whose quality is 0.75 and whose temperature is 312° F.? SOLUTION.—By Table 394, at 312° F.: $\mathbf{h} = 282$ B.t.u. per lb. $\mathbf{L} = 900.3$ B.t.u. per lb. $V_D = 5.47$ cu. ft. per lb. $P = 80$ lb. per sq. in. abs. Hence, by For. (242): the *total heat* $= \mathbf{H}_W = \mathbf{h} + \mathbf{xL} = 282 + (0.75 \times 900.3) = 957.2$ *B.t.u. per lb.* Now by For. (245), the *specific volume* $= V_W = \mathbf{x}V_D = 0.75 \times 5.47 = 4.10$ *cu. ft. per lb.* Hence, by For. (248), the *internal energy* $= \mathbf{I} = \mathbf{H} - 0.185{,}2\,PV = 957.2 - (0.185{,}2 \times 80 \times 4.10) = 896.4$ *B.t.u. per lb.*

370. Heat Energy Transfer May Be Expressed As The Product Of "Entropy" And "Absolute Temperature."—Every kind of energy or work may, as is explained below, be expressed as the product of two factors. Now, early in the study of heat phenomena it became evident to the investigator Clausius that it would be desirable to similarly express heat energy as the product of *two* factors. One of the factors he decided should be *absolute temperature.* The other factor, which he proposed—and which when multiplied by average absolute temperature would give heat energy—he named *entropy.* It might quite as well have been christened with any other distinctive name. Entropy will now be explained.

EXAMPLE.—*Illustrating How All Energy Change Is The Product Of Two Factors.* In representing energy by the area of a graph, one of these factors is represented by vertical distances and the other by horizontal distances. Thus, for example (Fig. 337):

(250) *Mechanical Energy Change* = (*Distance Change*) × (*Average Force*)

That is (Fig. 337), if it requires a force of 20 lb. to pull a weight, W, along a horizontal surface and the weight is pulled a distance of 40 ft. then: *the energy expenditure* $= 20 \times 40 = 800$ *ft.-lb.;* this 800 ft.-lb. of energy is represented by the area of $ABCD$ shown in Fig. 337-*II*. Also:

(251) *Mechanical Energy Change* = (*Volume Change*) × (*Average Pressure*)

That is, if the expanding steam in the engine cylinder, C, of Fig. 338 moves the engine piston, P, through a volume of 1.8 cu. ft. and the mean effective pressure from B to E (as determined with a steam-engine

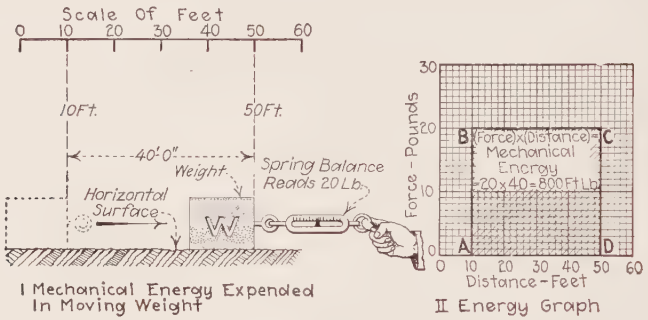

Fig. 337.—Showing how the product of two factors "force" and "distance" equals "mechanical energy" and how they may be employed in representing mechanical energy as an area.

indicator) is 10,282 lb. per sq. ft., then the mechanical energy expended by the steam (Sec. 99) will be: *External work = pressure × change in volume* = 10,282 × 1.8 = 18,507 *ft.-lb.* (The work done, if any, in pushing the exhaust steam out of right end of the cylinder, L, is here disregarded.) This energy expenditure—18,507 ft.-lb.—is represented

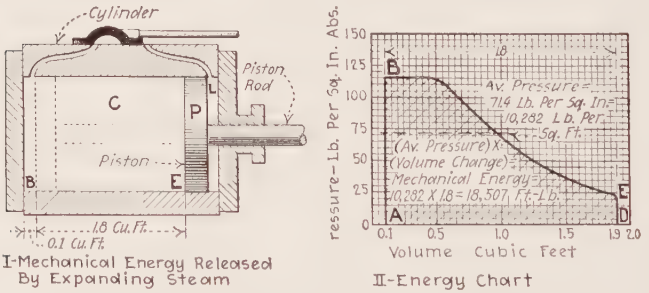

Fig. 338.—Showing how the product of two factors "pressure" and "volume" equals "mechanical energy" and how they may be employed in representing mechanical energy as an area.

by the shaded area $ABED$ within the diagram of Fig. 338-*II*. This is similar to any steam-engine indicator diagram for ½ a revolution. Also, in similar manner, it can be demonstrated that:

(252) *Hydraulic Energy Change* = (*Weight of Water Change*) × (*Average Height*)

And also:

(253) *Electrical Energy Change* = (*Quantity of Electricity Change*) × *Average Voltage*)

And, it can also be shown that for both of these forms of energy—Fors. (252) and (253) above –that the product of the two factors may be represented by an area. Now *heat is also a form of energy and, likewise, any change in it is the product of two factors and may be represented by an area.* As above stated, one of these factors is *average absolute temperature;* the other is called *entropy.*

Thus:

(254) *Heat energy change* = (*Entropy change*) × (*Average Abs. Temp.*)

The following example (Fig. 339) illustrates the application of the above equation. EXAMPLE.—In Fig. 339-*I* the 1 lb. of water, *L*, is at

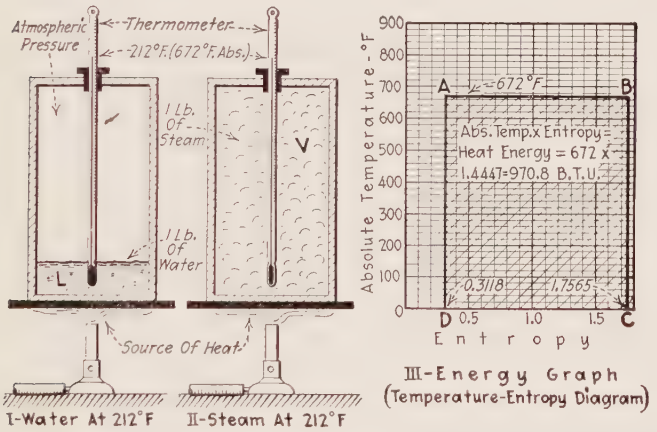

FIG. 339.—Showing how the product of two factors "absolute temperature" and "entropy" equals "heat energy" and how they may be employed in representing heat energy as an area.

212° F. (672° F. abs.). Now, heat is added until all of this water is vaporized into 1 lb. of steam *V*, at 212° F. (672° F. abs.) and atmospheric pressure. Compute, using entropy and absolute-temperature values, the heat energy which has been added as heat to the water, *L*, to thus vaporize it into steam, *V*, and also represent as an area on a graph this added heat energy. SOLUTION.—Now from Steam Table 394, horizontally opposite "212° F.," it is found that the entropy of 1 lb. of the liquid—water—is 0.311,8; also it is found that the entropy of 1 lb. of the vapor, *V* (steam) at 212° F. is 1.756,5. The temperature does not change while a liquid is being vaporized (Sec. 322); hence: *The average absolute temperature* = 212 + 460 = 672° F. *abs.* Therefore, to produce this

vaporization: *The heat energy transfer* = (*Entropy change*) × (*Av. abs. temp.*) = (1.756,5 − 0.311,8) × 672 = 1.444,7 × 672 = 970.8 *B.t.u.* This heat energy transfer is shown graphically in Fig. 339-*II* in which the shaded area *ABCD* is equivalent to the heat energy which was transferred.

The discrepancy between this value "970.8" and that given in Steam Table 394 of "970.4" is due to the usual assumption which was made in this example, that absolute zero is at −460° F.; actually it is at −459.6° F. instead of as given in the example.

This (Fig. 339) illustrates the simplest form of temperature-entropy problem—but the general principle which it discloses holds for all temperature-entropy problems. The example of Fig. 339 is simple because the temperature *AB* remains constant during the heat transfer. Except during changes of state (Fig. 339 for example) and during isothermal expansions, the temperature does change while heat energy is being transferred, as heat. When the temperature changes during heat transfer, the line on the corresponding temperature-entropy graph, which corresponds to the line *AB* Fig. 339, is not generally straight but becomes a curve. This is further explained hereinafter.

371. A Good General Definition of Entropy Change is *heat-energy transfer to or from a substance, per degree of average absolute temperature.* By "heat-energy transfer" is here meant energy which is transferred, *as heat*, from the substance to some external object, energy which is transferred, *as heat*, from some external source to the substance, or heat which is transferred within the substance itself due to *friction* of the substance. As is explained in the following note, entropy does not recognize heat energy which is due to external work. Also, the "average absolute temperature," as will be shown, must be determined in accordance with certain rules; it is the average of all of the absolute temperatures to which the substance has been subjected. It is *not* merely the mean of the initial and the final temperatures.

Note.—Entropy Is A Property Of Substances And Does Not Change When Internal Energy Is Transformed Into External Work.—If the substance at some definite condition is assumed as a starting point, it can be proved that, in passing to a second condition during a condition change, the entropy change will have a certain value, regardless of how the change was effected. This would not be true of the work done or heat added during the change. Since entropy change is dependent only on the initial and final conditions of the substance, it follows that entropy is a property of the substance.

Now, when internal energy is transformed into external mechanical work during a frictionless adiabatic (or isentropic, Sec. 385) condition change (no heat being interchanged between the substance and external objects, and no heat being generated by friction of the substance), there is no entropy change because there is no heat transfer. But, since internal energy is transformed into external work, the total heat (Sec. 108) of the substance must be reduced. Hence, entropy does not recognize heat energy which is due to external work.

372. Entropy Is Imperceptible To The Senses; its effects cannot be measured with instruments. Entropy values can be determined only by computation. The values of all other thermal properties of substances, such for example as temperature and pressure, *can* be measured with instruments. For these reasons, the significance of entropy may be difficult to understand. But if an entropy value is thought of merely as a previously determined multiplier, factor, or coefficient, which varies with the thermal condition of a substance, then the entropy idea should give no trouble. It is really not necessary—but it is desirable—to understand what entropy is, in order to use entropy values. In practice, values for entropy changes are usually taken from vapor-property tables (which practically always give entropy values for 1 lb. of the substance); for examples see Tables 394 and 395.

Note.—Any Substance Which Contains Heat Will Have Entropy.—However, it is a fact that the entropy idea is employed most frequently in connection with discussions of the thermal performance of gases and vapors—for which reason the treatment of entropy for the present book is included in this division. Another reason for the introduction of this treatment here is that it is desirable to understand "entropy" before using the entropy values which are given in the following tables of vapor properties.

373. The Principal Uses Of Entropy are: (1) *It renders possible the representation as an area on a graph, the heat energy which is transferred, as heat, to or from a substance.* The diagrams (see Fig. 339-*III* and following similar illustrations) which represent heat as an area are called *temperature-entropy* diagrams. These diagrams are useful in picturing the heat-energy transfers and cycles (see Div. 12) which occur in an engine or during any desired vapor or gas process; they provide a graphic presentation of the ideas which are involved and

relieve the mind of the necessity of holding, or of endeavoring to follow, a multitude of simultaneous conceptions. Temperature-entropy diagrams are ordinarily of little or no use to the practical operating engineer. (2) *It renders possible the plotting of heat-entropy charts* (Fig. 343) *and temperature-entropy charts.* From these charts the values of the various properties of the vapor, as the values change during frictionless adiabatic (isentropic) expansions, (Sec. 385) may be read directly. These changes in properties could not be plotted in this way on the charts without employing entropy—and they could not be determined except from the charts or by employing entropy without many complicated calculations.

374. The Absolute Entropy Of A Substance at any condition would be the total heat energy transferred to it, as heat, per degree of average absolute temperature to bring it to that condition. This "degree of average absolute temperature" would be the average of all of the absolute temperatures which the substance experienced from the condition of zero heat content up to the temperature of the stated condition. But it is impossible to determine the absolute entropy of a substance —in fact, it is always infinite—because nothing definite is known concerning the total heat contents of substances, or of their specific heats at very low temperatures. However, this does not affect the usefulness of entropy. In practice it is, as will be shown, *changes in entropy* at the temperature of practice that are always of interest, rather than absolute entropy. Only changes of entropy enter into heat transfers.

Note.—The Zero Of Entropy, In Dealing With Vapors, is arbitrarily taken as the absolute entropy—whatever it may be—of the liquid substance at 32° F. That is, the change that the entropy of a vaporous substance undergoes during any process wherein its condition is changed from the liquid state at 32° F., is said to be its entropy at the end of the process (at its final condition). The liquid state at 32° F., since it has been taken as the starting point or arbitrary zero of heat content (Sec. 108), is also for this reason a very convenient starting point for the measurement of entropy. Understand that this 32° F. is, for entropy, also an arbitrary or selected starting point.

Note.—"Absolute Entropy" Should Not Be Confused With "Total Entropy."—Total entropy (symbol n_D or n_S), as given in the vapor-property tables, is generally understood to mean the sum of the

entropy per pound of the liquid, n_L; *the entropy per pound of vaporization,* n_V; and *the entropy per pound of superheat,* n_S if any —all measured from the arbitrary zero as stated above. Two or all three of these entropy values are usually given in tables of vapor properties; see Table 394 for example.

375. The "Change In Entropy" Of A Substance, *between two thermal conditions, is the heat energy transferred to the substance, as heat, per degree of average absolute temperature between the two conditions.* Or, in other words: The change in entropy between two thermal conditions is a value such than when it is multiplied by the proper average of all of the absolute temperatures which the substance experienced during the heat transfer between the two conditions, it will give as a product the total heat energy added to or abstracted from the substance—as heat—during the transfer. See also the notes and explanations below.

376. The General Formulas For Entropy Change during a heat transfer (their derivation follows from the definitions given in Sec. 375) are:

$$Q = \frac{n}{T_A} \qquad \text{(B.t.u. per lb.)} \tag{255}$$

or

$$n = \frac{Q}{T_A} \qquad \text{(B.t.u. per lb. per avg. abs. ° F.)} \tag{256}$$

and

$$T_A = \frac{Q}{n} \qquad \text{(average abs. ° F.)} \tag{257}$$

Wherein: Q = heat-energy change, as heat, per pound of the substance during the heat transfer. T_A = *average* absolute temperature, during the heat transfer; that is; the average of *all* of the absolute temperatures to which the substance has been subjected during the transfer. n = change in entropy during the heat transfer. Note that Q may be expressed in any heat-energy unit and that T_A may be expressed in any absolute-temperature unit, then the entropy change, n, will be in terms of the quotient of these two units. But when Q is in British thermal units per pound and T_A is in average absolute degrees Fahrenheit, then n will be in British thermal

units per pound per average absolute Fahrenheit degree, as indicated after each of the above equations.

Note.—Entropy Recognizes Only Energy Which Is Added Or Abstracted As Heat—because of the definition of entropy. It does not recognize energy which is added to a substance by mechanical work being done on the substance, in spite of the fact that such energy may ultimately be converted to heat within the substance. Nor does entropy recognize energy which is lost from a substance by virtue of the doing of mechanical work by the substance. Thus, *during the frictionless adiabatic* isentropic, Sec. 385, *expansion or compression* (Sec. 388) *of a vapor or a gas there is no change of entropy* of the vapor or gas. If mechanical work is done in compressing a gas, adiabatically and without friction, the temperature of the gas will be increased thereby but the entropy of the vapor or gas will not be changed during the process, because no heat energy is added as heat. Similarly, when a vapor or gas expands adiabatically and without friction it will do mechanical work but there will be no change in entropy because in the process no energy has been lost as heat. (It is apparent then that *entropy recognizes only vibration heat, Sec.* 97, *and disgregation* heat, Sec. 98; it does not recognize external-work heat.)

377. How The Value Of The Change In Entropy For A Heat Transfer May Be Determined will now be explained in connection with Fig. 340. Entropy-change values seldom, if ever, have to be thus computed in practice because they are given in the vapor tables. The following approximate method is presented only to insure that the reader may have a better conception of the entropy idea. It is not given as a method to be followed in practice.

Explanation.—For simplicity consider 1 lb. of a substance which is assumed to have a specific heat of "1." Assume that it is heated from 32° F. (492° F. abs.) to 352° F. (812° F. abs.). Assume that the state of the substance does not change. It will be shown (Fig. 340) how the entropy of this substance increases as the heat energy is added to it, as heat, in 10 B.t.u. increments. The first 10 B.t.u. of heat which is added will, since the specific heat is "1" raise its temperature by 10° or from 492° F. to 502° F. abs. as indicated at *D*, Fig. 340. Now, by For. (256): $\mathbf{n} = Q/T_A$. The heat energy added, Q, is 10 B.t.u. During this addition, the average absolute temperature may, since the increase in temperature for each increment is small, be taken as ½ (*initial temperature* + *final temperature*), for each increment. Hence: $T_A = (492 + 502) \div 2 = 497°$ *F. abs.* Therefore, $\mathbf{n} = 10 \div 497 = 0.020,1$ *B.t.u. per lb. per avg.* ° F. *abs.* Now the distance *AC* is made to scale equal to 0.020,1. The

area, 1, (Fig. 340) will then be equivalent to the 10 B.t.u. of heat which was added—because: $0.020{,}1 \times 497 = 10$ *B.t.u.*

Similarly, the next heat-energy addition of 10 B.t.u., which will raise the temperature of the substance from 502 to 512° F. abs., will be represented in Fig. 340 by the area 2. Thus: $\mathbf{n} = Q/T_A = 10 \div [(502. + 512.) \div 2] = 10 \div 507 = 0.019{,}7$ *B.t.u. per lb. per avg.* ° F. *abs.* Therefore, area 2 is layed out 0.019,7 entropy units wide.

In like manner, the change in entropy due to each successive 10-B.t.u. heat-energy increment can be found and plotted on the graph.

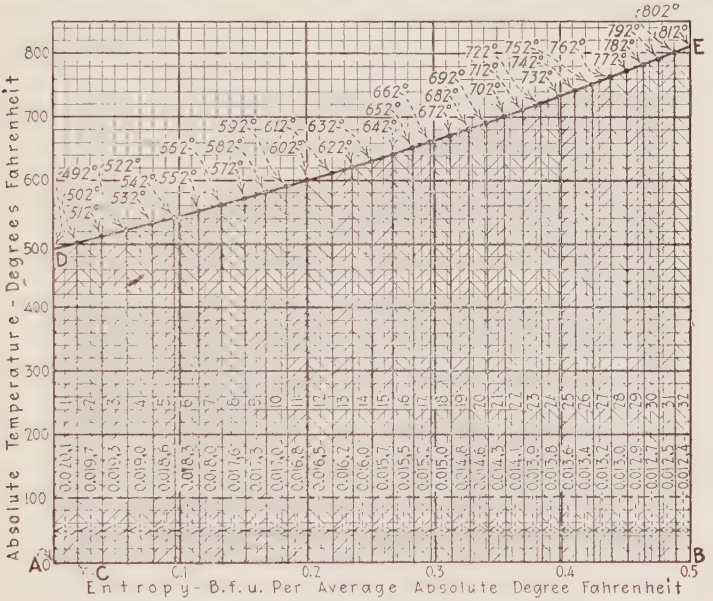

Fig. 340.—Illustrating the method of computing entropy.

Now note that while the *areas* of each of the strips 1, 2, 3 . . . 31, 32 are equal, and that each is equivalent to a heat addition of 10 B.t.u., the *widths* of the strips decrease toward the right. It is obvious that this decrease is necessary because, since the heights (temperatures) of the strips increase as heat is added, the widths of the strips must decrease if their areas are to be all equal. The total entropy change for this total heat addition of $10 \times 32 = 320$ *B.t.u.* is 0.5 B.t.u. per avg-° F. abs., as shown by the distance *AB*.

It should be understood that the method above described is an approximate one. Its degree of accuracy is determined by the smallness of the heat increments—the smaller the increments the more accurate the result. By applying the calculus the heat increments may be made infinitely small, whereby the entropy change can be determined with

absolute accuracy. The small error which results from the application of the method of Fig. 340 is due to the assumption that the short line connecting any two temperature increment points on the curve *DE*, is a straight line—whereas actually it is a curve.

Note.—Change In Entropy For Change Of State is exactly equal to the heat transfer divided by the absolute temperature at which the change of state occurs. This follows since the temperature always remains constant (Sec. 96) during a change of state, under which condition the "average temperature" must equal the constant temperature which obtains during the change. That is, for a change of state:

$$n = \frac{Q}{T} \qquad (258) \qquad \text{(B.t.u. per lb. per °F. abs.)}$$

378. Temperature-entropy Diagrams Show Heat Energy As An Area.—In the temperature-entropy diagram for steam shown in Fig. 341, all of the heat-energy transfers required

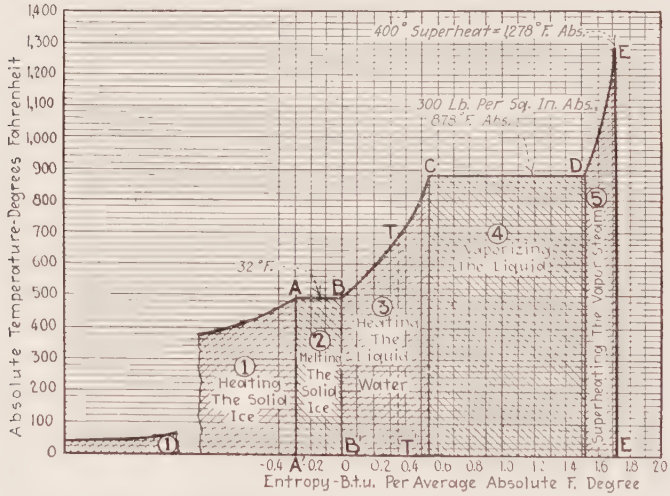

Fig. 341.—Temperature-entropy diagram showing the heat energy which must be added to change 1 lb. of ice into 1 lb. of superheated steam, comprising: (1) Heating the solid. (2) Melting the solid. (3) Heating the liquid. (4) Vaporizing the liquid. (5) Heating the vapor, called "superheating."

to change 1 lb. of ice from near absolute zero (−460° F.) into steam at a constant pressure of 300 lb. per sq. in. abs. and then into superheated steam at 1,278° F. abs. are shown. The plotted values are taken from Steam Tables 394 and 395.

Explanation.—At absolute zero the ice would contain no heat. If heat is transferred to the ice its temperature increases, the relation

being shown by the path OA. The area, 1, under this path, OA, represents the amount of heat-energy transfer required to heat the solid ice to the temperature at A. When A is reached, which is at 32° F. (492° F. abs.) any further addition of heat does not increase the temperature of the ice but causes it to melt—to change state. This melting continues until all of the ice is melted and the point, B, is reached. The area, 2, under AB, represents the amount of heat transfer required to melt the ice.

The addition of more heat causes the temperature of the substance—now water—to rise again at such a rate that the area under any portion of BC, as $B'BTT'$, represents the heat energy added during the change in temperature from 32° F. to the temperature T. The area, 3, under BC represents the heat-energy addition which was necessary to raise the temperature of the water from 32° F. to 418° F., or 878° F. abs.—which temperature is that of steam at a pressure of 300 lb. per sq. in. abs. This area 3, therefore, represents the heat of the liquid for steam at the pressure 300 lb. per sq. in. abs. After the temperature C is reached, which is the boiling temperature of the water for the 300 lb. per sq. in. pressure exerted upon it, any further addition of heat does not increase the temperature but again changes the state; it vaporizes the water into steam. Point D is reached when all of the water has vaporized. The area, 4, under CD represents the heat-energy addition necessary to vaporize the water—latent heat of vaporization. Now, as more heat is added to the steam (which is under constant pressure), its temperature increases following the curve, DE. The area, 5, under DE, represents the heat-energy addition required to superheat the steam at a pressure of 300 lb. per sq. in. to the temperature E which is 1,278° F. abs. If more heat energy is added to the steam, the curve DE will continue to rise until the steam begins to dissociate into its component elements, hydrogen and oxygen.

379. In Engineering, Only A Portion Of The Complete Temperature-entropy Diagram Is Used, as shown in Fig. 342. Since in engineering we are not concerned with vapors in the solid state only a part of the complete temperature-entropy diagram, which is shown in Fig. 341, is necessary to represent the heat transfers of vapor practice. The part which is most frequently used is that to the right of BB' in Fig. 341 or that shown in Fig. 342, that is only that part which concerns temperatures above the melting point.

EXPLANATION.—In both illustrations, (Figs. 341 and 342) the same path is shown: $BCDE$. The area $BCDEE'B'$ under this path represents the total heat energy required to change water at 32° F. to highly superheated steam (under a constant pressure of 300 lb. per sq. in. in abs.). This area represents the total heat as given in Steam

Table 395. The line *BHJL* (Fig. 342) represents the temperature-entropy path under a different pressure, 50 lb. per sq. in. abs. When more than one heating process is represented on the temperature-entropy plane, the resulting figure is called a *chart*. Such paths as *BHJL* and *BCDE* are called *constant-pressure lines*. The chart shows that, for different pressures, *the heat of the liquid, the latent heat of vaporization, and the heat required to superheat*, all are different.

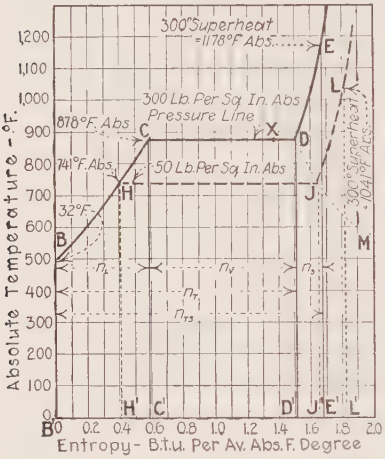

Fig. 342.—Temperature-entropy chart for 1 lb. of steam.

Note.—The Curved Line *DM* Is Called The "Dry Steam Line" (Fig. 342). It connects all points in the various constant-pressure lines which represent dry steam at the various temperatures (pressures). The water line, *BC*, and *DM* would intersect at the critical temperature, if they were extended upward. It should be remembered that this line *DM* is used for convenience to connect dry-saturated-vapor points; strictly, it is not a part of the temperature-entropy diagram and does not represent a physical process.

Note.—The Line *CD* Is Not Only A "Constant Temperature Line" But Is Also A "Constant Pressure Line" (Fig. 342). To the right of the point *D* the constant pressure line is not horizontal but is a rising curve, since at *D* the steam starts to become superheated.

380. The Values For The Entropy Of Vapors At Different Conditions Are Given In The Vapor Tables (Table 394) with the other vapor properties. Besides *the total entropy* there is also usually given *the entropy of the liquid and the entropy of vaporization*. The entropy of the liquid is graphically represented by the distance n_L (Fig. 342) and the entropy of vaporization by the distance n_V, for the given pressure. The *total entropy for dry saturated steam* is represented by the sum of the two or by the distance n_T. The total *entropy of superheated vapors* is given in the tables of superheated vapors (Table 395) and is represented by n_{TS} in Fig. 342. The entropy of superheat (n_S, Fig. 342) for a given degree of

superheat can be obtained by subtracting the entropy of dry saturated vapor, which is at the same pressure as the superheated vapor, from that of the superheated vapor.

381. The Total Entropy For A Wet Vapor Cannot Be Obtained Directly From The Vapor Tables.—It can, however, be calculated when the quality of the steam is known by the following formula:

(259) $\mathbf{n}_W = \mathbf{n}_L + \mathbf{x}\mathbf{n}_V$ (B.t.u. per lb. per avg. abs. ° F.)

Wherein: $\mathbf{n}_W$ = total entropy for 1 lb. of wet vapor. $\mathbf{n}_L$ = entropy for 1 lb. of liquid at the same pressure, as taken from the vapor-property table. $\mathbf{n}_V$ = entropy of vaporization for 1 lb. of vapor at the same pressure, as taken from the vapor property table. $\mathbf{x}$ = quality of the vapor expressed decimally. The application of this formula is illustrated in following Probs. 4 and 5, see appendix for solutions.

DERIVATION.—In any temperature-entropy diagram showing the vaporization of a liquid: *Entropy change of vaporization* = (*Latent heat of vaporization*) ÷ (*Absolute temperature*). Thus in Fig. 342, $\mathbf{n}_V$ = (*Latent heat of vaporization of the dry steam*) ÷ (*Absolute temperature*). When the vapor is wet all of the latent heat of dry steam is not used but the temperature remains the same as that of dry steam. Hence, when the vapor is wet, the entropy change of vaporization will be less than that for dry steam and D will (Fig. 342) move to some point X. Consequently, for wet steam: *The Entropy change*, CX = (*Latent heat of vaporization of wet steam*) ÷ (*Absolute temperature*). Since, as stated above and as is evident from Fig. 342, the "*Absolute temperature*" is the same for both of the two above equations, it is evident that:

(260) $$\frac{CX}{\mathbf{n}_V} = \frac{\textit{Latent heat of the wet steam}}{\textit{Latent heat of the dry steam}}$$

Now (see Sec. 366) if $\mathbf{x}$ represents the quality expressed decimally, then:

(261) $$\frac{\textit{Latent heat of the wet steam}}{\textit{Latent heat of the dry steam}} = \mathbf{x}$$

Hence, substituting in For. (260) the equivalent from For. (261) there results:

(262) $$\frac{CX}{\mathbf{n}_V} = \mathbf{x};\ \text{or},\ CX = \mathbf{x}\mathbf{n}_V$$

Now, as is evident from Fig. 342, the total entropy change of the wet vapor, which will be here designated by $\mathbf{n}_W$, equals the sum of $\mathbf{n}_L + CX$. That is:

(263) $$\mathbf{n}_W = \mathbf{n}_L + CX$$

Now, substituting in For. (263) the equivalent for CX from For. (262), there results:

$$\mathbf{n}_W = \mathbf{n}_L + \mathbf{x}\mathbf{n}_V \tag{264}$$

Which is the same as For. (259).

Note.—The Quality Can Be Determined, If $\mathbf{n}_T$ And $\mathbf{n}_L$ Are Known.—For, by transposing For. (259), we obtain:

$$\mathbf{x} = \frac{\mathbf{n}_W - \mathbf{n}_L}{\mathbf{n}_V} \quad \text{(decimal.)} \tag{265}$$

This is the relation which is useful in determining the quality of a vapor after a frictionless adiabatic (isentropic) expansion. In a frictionless adiabatic expansion $\mathbf{n}_W$ is known and $\mathbf{n}_L$ can be found from the vapor tables. The quality can also be obtained directly from the chart of Fig. 343. The application of this formula is illustrated in following Prob. 5; see appendix for solution.

382. The "Temperature-entropy" And The "Mollier" Or "Heat-entropy" Charts Are Graphs Which Show The Principal Properties Of A Vapor; see Fig. 343. Thus, the properties of a vapor can be represented on a graph for which entropy and temperature, or entropy and some other properties are employed as coordinates. These charts are especially useful in frictionless-adiabatic-expansion calculations. The employment of entropy in plotting these charts is, as explained in preceding Sec. 373, its most important practical application. The temperature-entropy chart is merely a combination of many temperature-entropy diagrams as shown in Fig. 341. The Mollier diagram or heat chart (Fig. 343) uses *entropy* and *total heat content* as coordinates and, since in practical computations the total heat-content is generally desired, this is the most frequently used and the more convenient chart. From it the heat content, in British thermal units, can be read off directly. The heat-entropy chart resembles the temperature-entropy chart; it has the same lines only they have a different slope. It is, as is explained below, plotted in a manner similar to that employed for the temperature-entropy chart. In steam practice only the upper right-hand portion of a diagram such as that of Fig. 344 is needed in calculations; therefore, this is the only portion reproduced in the practical charts.

Explanation.—A Heat-entropy Or Mollier Chart May Be Constructed In The Following Manner.—For this chart (Fig. 343),

total heat and entropy are the two coordinates used and they should be plotted at right angles. Fig. 344 illustrates the process. The plotted values are from Steam Table 394. When the heat content is zero, the

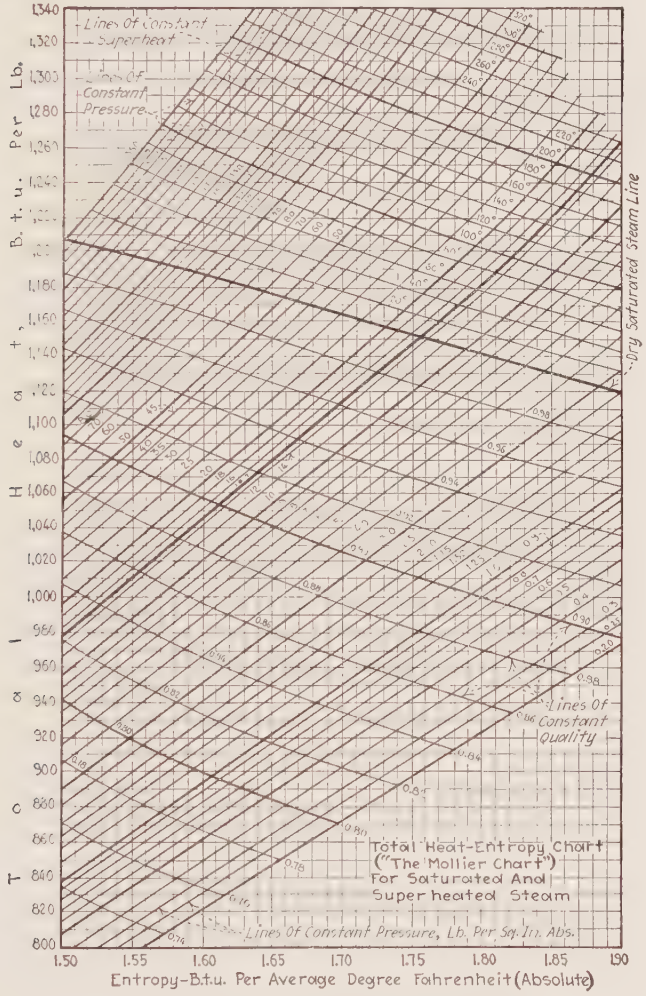

FIG. 343.—Total heat-entropy chart for steam.

entropy is zero. The usual practice of assuming an arbitrary zero, or datum for heat content and entropy, at 32° F. (Sec. 374) is here followed. Thus, the state of zero entropy and zero heat content starts at

O (Fig. 344), with water at 32° F. As heat is applied the entropy increases, the state point moves along the *liquid or water line OA* which is similar to that of the temperature-entropy diagram, *BC* Fig. 342. This line, *OA*, is obtained by plotting the heat-of-the-liquid values against the corresponding entropy-of-the-liquid values, as obtained from Steam Table 394 for various pressures. When evaporation begins as at *A*, the entropy increases in direct proportion to the heat added, so the evaporation line *AB* is straight. The point *B* is obtained by plotting the value of the total heat of dry saturated steam at 300 lb. per sq. in. abs. against the value of the corresponding entropy; both values are from Steam Table 394. During superheating, the entropy increases from *B* to *C* but

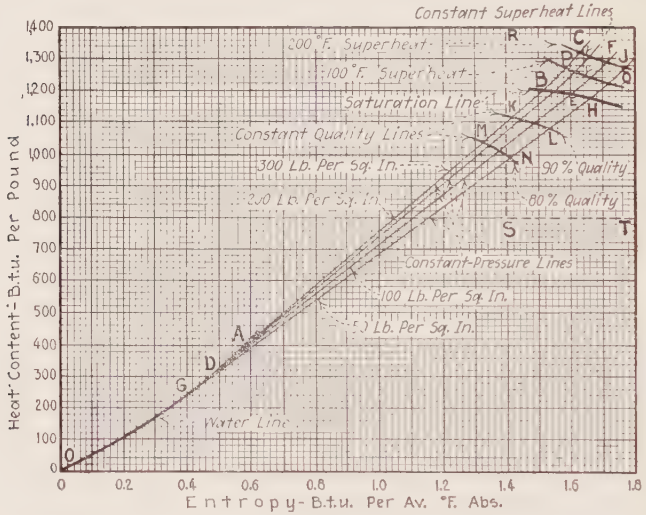

Fig. 344.—Showing how a heat-entropy or Mollier chart for steam is constructed.

not in direct proportion to the heat added, so the line *BC*, has a slight curvature. The line *BC* is obtained by plotting the values of the total heat of superheated steam against the corresponding entropy values for various degrees of superheat, but all at 300 lb. per sq. in. abs. pressure. These values are all obtained from Steam Table 395. The path followed *OABC* is the *line of constant pressure.*

Other constant pressure lines may be similarly drawn, such as *ODEF* and *OGHJ*. The points *B*, *E*, and *H*, which represent dry saturated steam on the various constant-pressure lines, are then connected by the line *BH*. This line is the 100 per cent. quality line or *saturation line.* It is the dividing line between the wet-steam region, the area below it, and the superheated-steam region, the area above.

The point, *K*, is chosen on the line *AB* so that the distance *AK*, divided by the distance *AB* equals 0.90; similarly, points are located on the other

constant-pressure lines. These points are then connected by the line *KL*, which is the 90 per cent. *constant-quality line*. Other constant quality lines may be drawn, such as *MN*.

Lines connecting points all of which have the same degree of superheat but which are located on the different constant-pressure lines are called *lines of constant superheat*. Such a line for 100° superheat is shown at *PQ*.

Horizontal lines on Fig. 344 represent constant heat content, and vertical lines constant entropy. Frictionless adiabatic (isentropic) processes are represented by the latter (see Sec. 385). The upper right-hand portion of Fig. 344, which is shown cut out by the dotted lines, is all that is reproduced in a practical heat-entropy chart (Fig. 343) because the remaining portion of Fig. 344 would never be used. Lines of constant volume may be, but seldom are, plotted on the same chart with the properties of Fig. 344 because too many lines on one chart make it difficult to read.

383. There Are An Infinite Number Of Ways In Which A Vapor Can Expand Or Be Compressed just as there are an infinite number of ways in which a gas can expand or be com-

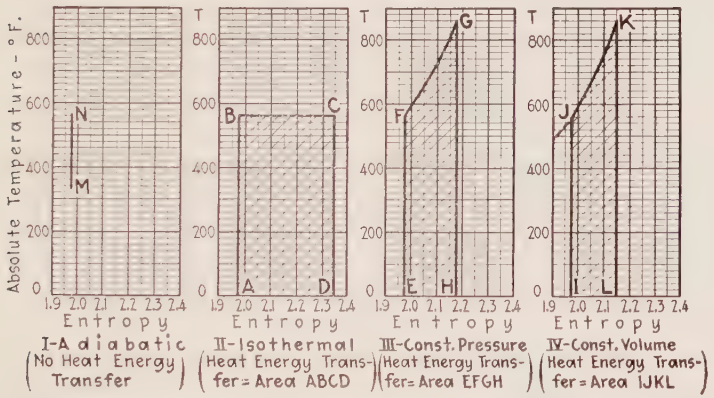

Fig. 345.—Showing characteristic temperature-entropy graphs for adiabatic (isentropic), isothermal, constant-pressure, and constant-volume processes.

pressed (Div. 8). Of this infinite number, only three ideal ways (Fig. 345), a knowledge of which is useful because close approximations of them occur in practical heat phenomena, will be treated here.

Note.—In A Sense It May Be Considered That There Are Only Two Fundamental Ways In Which A Vapor Or Gas Can Expand. (1) *Isothermal* or at constant temperature, Fig. 345-*II*. (2) *Isentropic*,

Sec. 385 or at constant entropy, Fig. 345-*I*. All other expansions lie somewhere between these two as limits and all others, may in a sense be considered as the simultaneous occurrence of these two in various combinations. The slope of any expansion line, as *FG* (Fig. 345), is determined by the specific heat of the substance under the given conditions.

384. The Expansions Of Vapors, Close Approximations Of Which Ordinarily Occur In Practice are: (1) *Frictionless adiabatic (isentropic) expansion.* (2) *Constant-pressure expansion.* (3) *Constant-heat-content expansion* or *throttling.* These are ideal ways of expansion for various processes and while they are in these certain processes generally closely approximated in practice, they are never actually obtained. The characteristics of these ideal expansions are given in the following sections.

Note.—The Line Of Constant Volume, sometimes called the constant-volume expansion line *JK*, Fig. 345-*IV*, does not really represent an expansion since no change in volume takes place. However the area *IJKL* does represent the heat-energy transfer necessary to raise the temperature of the vapor from *J* to *K* at constant volume. This line, *JK*, is the dividing line between compressions and expansions. Any line drawn through a point, as *J*, so that if falls (no matter what its direction) to the lower right of the constant volume line *JK* represents some expansion process. Likewise any line through *J* falling to the upper left of *JK* represents some compression process. Any number of both such lines are possible for various expansion and compression processes.

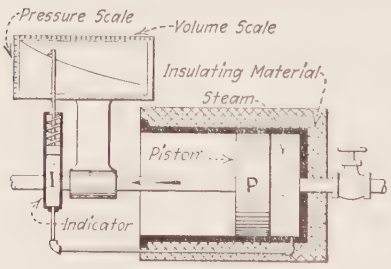

Fig. 346.—Representing an adiabatic isentropic expansion of water vapor—steam. (The expansion is rapid. Work is done by piston *P*. The insulating material prevents transfer of heat, as heat, during the expansion. An indicator, *I*, gives a deflection proportional to the pressure.)

385. An Isentropic Or Frictionless Adiabatic Expansion Of A Vapor is that expansion in which (Fig. 346), the entropy of the vapor remains constant; it is a *constant-entropy expansion.* On a temperature-entropy diagram (or on a heat-entropy diagram), it is represented by a vertical straight line (*MN*, Fig. 345). During this expansion the vapor does mechanical work but receives or gives off no heat energy, as heat, from or

to external sources or due to internal friction during the expansion. This expansion corresponds to the frictionless adiabatic expansion of a perfect gas as defined in Sec. 272. An isentropic expansion is often called simply "an adiabatic" expansion, but, strictly speaking, this term is not correct. The term "adiabatic" may mean a whole family of changes in which no heat transfer to or from external objects takes place; the isentropic expansion is but one of these. *The isentropic expansion is generally assumed as the ideal for vapor engines* (Div. 12) because, as shown below, it is the expansion during which the greatest possible amount of the heat energy in a substance at a given temperature is converted into external work. Isentropic expansions are approached in the steam-engine cylinder and in the steam-turbine nozzles.

Explanation.—That the maximum heat energy will be converted into mechanical work by an isentropic adiabatic expansion will be evident by referring to Fig. 347. The line AB represents, to scale, the isentropic expansion of 1 cu. ft. of dry saturated steam at 308° F. until its temperature falls to 162° F. By Sec. 262, (Division 8) the shaded area under AB represents the work done by the steam during its expansion. Suppose that another expansion, during which heat is abstracted from the steam, is represented by another line AC. Then AC must fall to the left of AB because, at any pressure during the expansion the quality of the steam, and hence the volume, will be less than during the isentropic expansion —because of the extracted heat. Hence the area under any such expansion graph (shaded dark) will be less than that under AB—less work will be done than by the isentropic expansion. The only way that the expansion graph could be made to fall to the right of AB would be by adding heat during the expansion process As will be explained (Div. 12), this would be a less efficient process. Therefore, the isentropic expansion is often taken as an "ideal" in heat-engine calculations.

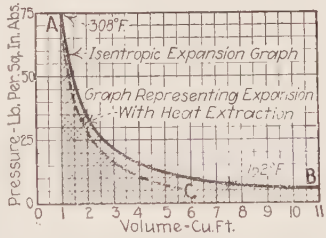

Fig. 347.—Pressure-volume graphs showing that an isentropic expansion extracts (as external work) more heat than any other expansion during which no heat is added to the substance. The graphs are drawn for steam expanding to 162° F. from the dry saturated condition at 308° F.

Note.—The Condition Changes Which Accompany Isentropic Expansions Of Vapors may be read from their temperature-entropy diagrams which show that constant-entropy or isentropic expansion of

dry vapor causes wetness; of superheated vapor, causes loss of superheat; and of very wet vapor causes drying. Thus, from Fig. 342, it is evident that the isentropic expansion of dry saturated water vapor (steam) from any pressure, as for example downward along *DD'*, will result in wet steam (Sec. 355). This is because any point below *the saturation line*, *DM*, lies in an area which represents wet steam. It is also similarly evident that the isentropic expansion of superheated steam at any pressure and degree of superheat, such as represented by a path downward along *EE'*, results in a loss of superheat and if the expansion is continued, wet steam will likewise result. For wet steam with a quality less than about 50 per cent., the quality lines (Sec. 382) slope in the same general direction as the water line, *BC*. Hence, if an isentropic expansion starts with very wet steam (a quality of less than about 50 per cent.) drier steam will result. That is, following downward along the line *CC'* (Fig. 342), the quality of the steam increases. *Ether is an exception* to the first two of the above statements in that the isentropic expansion of its dry vapor causes superheat and the isentropic expansion of its superheated vapor causes greater superheat.

Note.—To Determine From The Heat-entrophy Chart, Fig. 343, The Quality Of Steam After Isentropic Expansion, proceed thus. Suppose it is desired to find the quality of superheated steam after isentropic expansion from a pressure of 200 lb. per sq. in. abs. and at 200° F. superheat to a pressure of 1.5 lb. per sq. in. abs. Start at the intersection of the 200 lb. per sq. in. abs. constant pressure and 200° F. superheat lines. Then follow vertically down the constant-entropy line until the 1.5 lb. per sq. in. abs. constant-pressure line is reached. The point thus located is between the 84 and 85 per cent. constant quality lines. The distance between the point and the 84 per cent. constant quality line is about $\frac{2}{5}$ of the total distance between the 84 and 85 per cent. constant-quality lines. Thus the *quality* = $84\frac{2}{5}$ or 84.4 *per cent.*

386. Constant-pressure Expansion (Fig. 345-*III*), as the name implies, is expansion against a constant pressure. This is the expansion that takes place in a boiler when water is vaporized. It also takes place in a superheater where vapor is heated at constant pressure. It occurs in the cooling coil of a refrigerating plant. But the cooling coil in a refrigerating plant is analogous to the boiler and superheater in a steam plant, since in it the liquid absorbs heat from the room or body which is to be cooled.

387. Constant-heat Expansion (Fig. 348) sometimes called "*wire-drawing*" or "*throttling*," as the name implies, means expansion during which the heat-content of the vapor does not change. It occurs when a vapor expands from a high-

pressure through a small crack or orifice to a lower pressure so that the only mechanical work done is that expended in overcoming friction. But this friction work merely heats the orifice and surroundings so the heat thereof is reabsorbed by the vapor. Thus the heat content per pound of vapor is the same after expansion as before expansion.

Examples.—This constant-heat expansion occurs in the throttling calorimeter (Sec. 392). It takes place also to some extent in undersized pipes and partly opened valves. It cannot be used advantageously in engines since in it no heat is converted into work. It is employed in refrigeration (Sec. 632) where the pressure on the refrigerant is lowered by permitting the refrigerant liquid which is under high pressure to expand through an orifice into a space where the pressure is much lower.

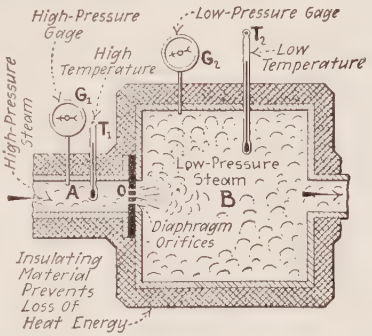

Fig. 348.—Constant-heat or Joule-Thompson expansion, also called wire drawing and throttling. (The steam passes from the high-pressure, G_1, and temperature, T_1, conditions in, A, to the low-pressure, G_2, and temperature, T_2, conditions in B, without loss of heat content.

388. Compression Of Vapors Occurs Ordinarily In One Of Three Ways or in some combination of them: (1) *Isentropic or constant-entropy* compression. (2) *Isodynamic or constant-internal energy* compression. (3) *Constant-pressure compression.* As with the expansion of vapors (Sec. 383) there are an infinite number of ways of compression. *Isentropic compression* is the reverse of isentropic expansion. In it, the largest possible amount of mechanical work is changed into heat energy but no heat is added to or abstracted from the vapor as heat. Thus the internal energy of the vapor is increased. Since in vapor compression it is not desired to change a maximum of mechanical work into heat, but instead to change a minimum of mechanical work into heat, adiabatic compression instead of being an ideal compression is the least desired of all compressions. *Isodynamic compression* is that compression during which the internal energy in the vapor remains constant. This may (theoretically but not practically) be obtained by absorb-

ing heat from the vapor with cooling water at the same rate as the mechanical work is done. It is the ideal compression for refrigerants as the mechanical work done during it in the compression from one state to another is less than that done during any other compression. *Constant-pressure compression* is the reverse of constant-pressure expansion; it is compression or contraction which occurs at constant pressure. This compression takes place in a condenser when a vapor is condensed.

389. The Energy Relations During An Isentropic Process may be found from the following formulas which are derived as shown below. The pressure-volume relations may be computed from values found on the constant-entropy line on the total heat-entropy chart (Fig. 343). The energy relations are:

(266) $\mathbf{Q} = 0$ (heat added)

(267) $\mathbf{Q}_I = \mathbf{I}_2 - \mathbf{I}_1$ (B.t.u. per lb.)

(268) $W_E = 778\,(\mathbf{I}_1 - \mathbf{I}_2)$ (ft.-lb. per lb. of vapor)

(269) $W_E = 778\,(\mathbf{H}_1 - \mathbf{H}_2) + 144(P_2V_2 - P_1V_1)$ (ft.-lb. per lb. of vapor)

Wherein: $\mathbf{Q}$ = the heat added during the process. W_E = the external work done *by* the vapor during the process, in foot-pounds per pound of vapor. $\mathbf{Q}_I$ = the change in internal energy during the process, in British thermal units per pound of vapor. $\mathbf{I}_1$ and $\mathbf{I}_2$ = respectively, the internal energy of the vapor at the beginning and end of the process, in British thermal units per pound. $\mathbf{H}_1$ and $\mathbf{H}_2$ = respectively the heat contents of the vapor at the beginning and end of the process, in British thermal units per pound. P_1 and P_2 = respectively, the pressures of the vapor at the beginning and end of the process, in pounds per square inch absolute. V_1 and V_2 = respectively, the specific volumes of the vapor at the beginning and end of the process, in cubic feet per pound.

Derivation.—Since, by definition, no heat is added to or abstracted from the substance during an isentropic process, For. (266), which expresses this fact mathematically, must hold. Now, by For. (58), for any condition change

(270) $$Q = Q_I + Q_E \quad \text{(B.t.u.)}$$

Hence, by combining Fors. (266) and (270), there results

(271) $$0 = Q_I + Q_E \quad \text{(B.t.u.)}$$

or, by transposing

(272) $$Q_E = -Q_I \quad \text{(B.t.u.)}$$

Now, it is evident that For. (267) expresses the value of Q_I. Hence, by combining Fors. (267) and (272), there results:

(273) $$Q_E = -(I_2 - I_1) = I_1 - I_2 \quad \text{(B.t.u.)}$$

But, by For. (46), $W_E = 778\ Q_E$. Hence:

(274) $$W_E = 778\ (I_1 - I_2) \quad \text{(ft.-lb.)}$$

Now, For. (249) gives the expressions for I_1 and I_2 which, when substituted in For. (274), give For. (269).

EXAMPLE.—How much work is done by 1 lb. of steam in a steam-engine cylinder during its expansion from 150 lb. per sq. in. gage (dry saturated) to 29.3 lb. per sq. in. gage? Assume that the expansion is isentropic. SOLUTION.—From Table 394, for 150 lb. per sq. in. gage: $H_D = 1{,}195.0$ B.t.u. per lb.; $n_D = 1.561{,}5$; $V_D = 2.753$ cu. ft. per lb. Also, for 29.3 lb. per sq. in. gage: $h = 242.0$ B.t.u. per lb.; $L = 929.2$ B.t.u. per lb.; $n_L = 0.400{,}2$; $n_V = 1.268{,}1$; $V_D = 9.59$ cu. ft. per lb. Now, since the entropy remains constant, the *quality* after expansion may be determined by For. (265), thus: $x = (n_W - n_L)/n_V = (1.561{,}5 - 0.400{,}2) \div 1.268{,}1 = 0.916$. Hence, by For. (242), the *total heat* after expansion $= H_W = h + xL = 242.0 + (0.916 + 929.2) = 1{,}093$ *B.t.u. per lb.* Also by For. (245), the *specific volume* after expansion $= V_W = xV_D = 0.916 \times 9.59 = 8.78$ *cu. ft. per. lb.* Now, by For. (269), the *work done* $= W_E = 778\ (H_1 - H_2) + 144\ (P_2V_2 - P_1V_1) = 778 \times (1{,}195 - 1{,}093) + \{144 \times [(44 \times 8.78) - (164.7 \times 2.753)]\} = 793{,}500 - 96{,}800 = 696{,}700$ *ft.-lb.*

EXAMPLE.—How much work is done on 1 lb. of ammonia vapor of quality 0.80 and at 30 lb. per sq. in. abs. in compressing it isentropically to ¼ its volume? SOLUTION.—Values for the several properties are taken from Table 399. By For. (259), the *entropy* $= n_W = n_L + xn_V = -0.070{,}9 + (0.80 \times 1.244{,}9) = 0.925{,}0$. By For. (245), the *specific volume before compression* $= V_W = xV_D = 0.80 \times 9.19 = 7.35$ *cu. ft. per lb.* Hence, the *specific volume after compression* $= V_2 = V_1/4 = 7.35 \div 4 = 1.838$ *cu. ft. per lb.* By trial, using Fors. (247) and (259), it is found that a specific volume of 1.838 cu. ft. per lb. corresponds at at 80° F. to a quality of 0.949 and an entropy of 0.987,5; at 75° F. to a quality of 0.872 and an entropy of 0.921,0. Hence, the *temperature after compression* $= 75 + 5\ [(0.925{,}0 - 0.921{,}0) \div (0.987{,}5 - 0.921{,}0)] = 75.3°$ F. Likewise, the *quality after compression* $= 0.877$ and the *pressure after compression* $= 142$ *lb. per sq. in. abs.* Hence, the *total heat after compression*, by For. (242), $= H_W = h + xL = 48.3 + (0.877 \times 507.8) = 493$ *B.t.u. per lb.* Likewise, the *total heat before compression* $= H_W = h + xL = -33.7 + (0.80 \times 572.2) = 414.1$ *B.t.u. per lb.* There-

fore, by For. (269), the *work done* = $W_E = 778\ (H_1 - H_2) + 144\ (P_2V_2 - P_1V_1) = 778 \times (414.1 - 493) + 144\ [(142 \times 1.838) - (30 \times 7.35)] = -61{,}380 + 5{,}832 = -55{,}548$ *ft.-lb.* Hence, the *work done on the vapor* = 55,548 *ft.-lb.*

390. The Energy Relations During A Constant-pressure Process are quite simple. Since total heats, Secs. 365 to 367, represent heat additions at constant pressure they represent constant-pressure processes. Therefore, for constant-pressure processes the following formulas may be written:

(275) $\quad Q = H_2 - H_1$ (B.t.u. per lb.)

(276) $\quad Q_I = I_2 - I_1$ (B.t.u. per lb.)

(277) $\quad W_E = 144\ P\ (V_2 - V_1)$ (ft.-lb. per lb.)

Wherein: Q = the heat added to the substance, in British thermal units per pound. Q_I = the change in internal energy during the process, in British thermal units per pound. W_E = the external work done *by* each pound of vapor, in foot-pounds. H_1 and H_2 = the total heats, respectively, at the beginning and end of the process, in British thermal units per pound. I_1 and I_2 = respectively, the initial and final values of the internal energy of the vapor, in British thermal units per pound. P = the pressure of the vapor, in pounds per square inch absolute. V_1 and V_2 = the initial and final specific volumes of the vapor, respectively, in cubic feet per pound.

Example.—How much work is done by 1 lb. of steam as it evaporates in a boiler at 350° F. and is superheated to 500° F.? How much heat is added? Solution.—From Table 393, the specific volume of water at 350° F. is 0.018 *cu. ft. per lb.* From Table 395, by interpolating, the volume of 1 lb. of superheated steam at 134.6 lb. per sq. in. abs. and 150° F. superheat is 4.15 *cu. ft. per lb.* Hence, by For. (277), the *external work* = $W_E = 144\ P(V_2 - V_1) = 144 \times 134.6 \times (4.15 - 0.018) = 80{,}000$ *ft.-lb.* Also, the total heat of the superheated steam is $H_S = 1{,}272.2$ *B.t.u. per lb.* and, the heat of the liquid at 350° F. is 321.4 *B.t.u. per lb.* Hence, by For. (275), the *heat* added = $H_2 - H_1 = 1{,}272.2 - 321.4 =$ 950.8 *B.t.u. per lb.*

Example.—How much heat must be abstracted from 1 lb. of dry saturated ammonia at 85° F. in condensing it to the liquid state and how much external work is done by the ammonia in condensing? Solution. —By Table 299, $P = 167.4$ *lb. per sq. in. abs.* $V_D = 1.788$ *cu. ft. per lb.* $V_L = 0.027$ cu. ft. per lb. $H_D = 557.9$ *B.t.u. per lb.* $h = 59.4$

B.t.u. per lb. Hence, by For. (275), the *heat added* = $Q = H_2 - H_1 = 59.4 - 557.9 = -498.5$ *B.t.u. per lb.*; or, the *heat abstracted* = $-Q = 498.5$ *B.t.u. per lb.* Also, by For. (277), the *work done by the vapor* = $W_E = 144P(V_2 - V_1) = 144 \times 167.4 \times (0.027 - 1.788) = -42{,}450$ *ft. lb.*; or, the *work done on* the vapor = $-W_E = 42{,}450$ *ft.-lb.*

NOTE.—THE ENERGY RELATIONS DURING THROTTLING AND ISODYNAMIC PROCESSES are not required in engineering work. For a throttling process, as explained in Sec. 387, $Q = 0$, $W_E = 0$, and, therefore, $Q_I = 0$. For an isodynamic process, by definition, $Q_I = 0$; hence $Q = -W_E/778$.

391. The Characteristics Of Water Vapor—Steam—Make It The Best Medium Of All The Vapors For Transforming Heat Energy Into Mechanical Work.—The water from which it is formed is the cheapest and most plentiful of all liquids.

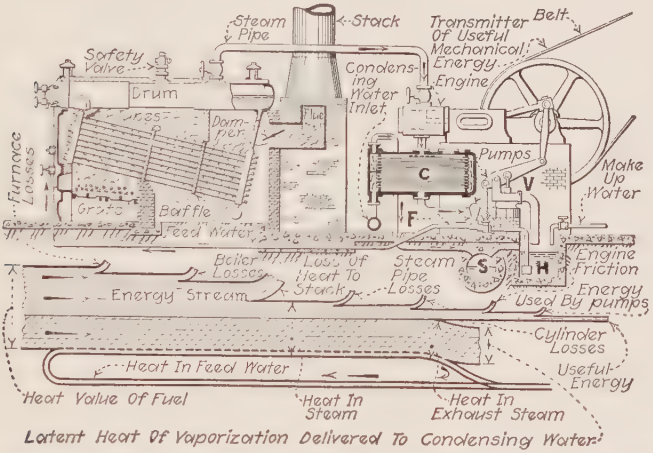

FIG. 349.—Latent heat of vaporization in steam-engine operation. (C = condenser. H = hot well. S = sewer. V = vacuum pump. F = feed pump.)

It is relatively non-corrosive and does not harm the interiors of boilers. The steam formed does not attack steel. It gives off no fumes that are harmful to the body. Another important property is that the water has a large latent heat of vaporization (see Sec. 323), almost twice that of any other vapor. This property of water makes it possible to transmit much heat (Fig. 349) with little liquid or vapor. The boiling temperatures of steam are fairly high with moderate pressures and since the efficiency of an engine depends on the tempera-

ture range through which it acts, this is a decided advantage. It is these characteristics of steam which have made it the one vapor used in preference to all others, for generating power.

Note.—Dry Saturated Or Superheated Steam Is Colorless And Transparent as are the colorless gases. The fog (Sec. 343) which one sees issuing from a steam exhaust pipe or from the mouth of a person in winter is really not steam. It is merely condensed water vapor—small particles of water—suspended for the moment in the atmosphere.

392. The Quality Of Steam Can Be Determined By Means Of A Throttling Calorimeter (Figs. 350 and 351), providing the steam is not very wet —the lowest quality determinable by

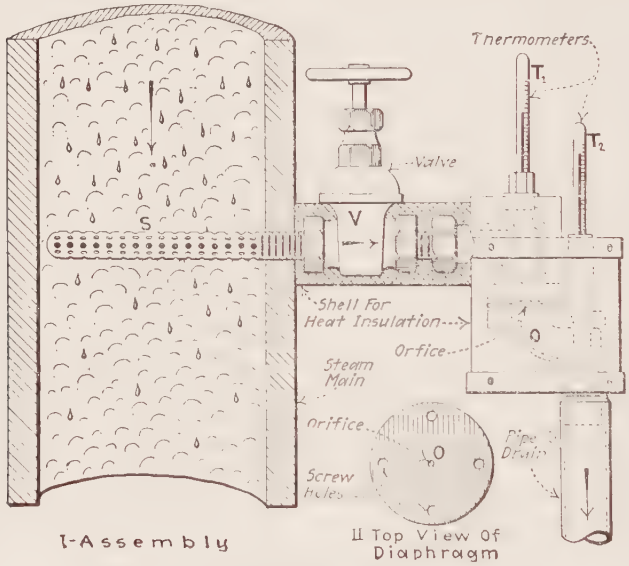

Fig. 350.—Barrus throttling steam calorimeter.

a throttling calorimeter ranges from about 94 per cent. at 300 lb. per sq. in. abs. to about 96.5 per cent. at 100 lb. per sq. in. abs. In plants using saturated steam, it is desirable to know the quality of the steam because the pressure alone does not determine its heat content. When a throttling calorimeter is used, a sample of the steam is obtained by means of a sampling tube, *S* (Fig. 350), extending almost across the steam main in which it is desired to determine the quality. The sampling tube has a uniform arrangement of small holes so that a repre-

sentative sample is obtained. The admission of the sample is controlled by valve, V. The temperature of the incoming steam is measured by a thermometer T_1. The steam then passes through a small hole or orifice, O, in the center of a circular plate, into the chamber, C, (Fig. 351). The orifice is so small (about $\frac{1}{16}$ in. in diameter) that the steam pressure is reduced by it to practically atmospheric pressure. The pressure, P_2, in C may be measured by a manometer, not shown, but it is generally only slightly more than atmospheric. The calorimeter is thoroughly lagged and, neglecting the small atmospheric rabiation loss, all the heat in the incoming steam, since no work is done by it, must be in the exhaust steam. Since the heat content of slightly wet steam at higher pressures is greater than that of saturated steam at atmospheric pressure, the exhaust steam will be superheated. When the calorimeter is in use, V is opened wide and the temperature of the exhaust is read from the thermometer T_2.

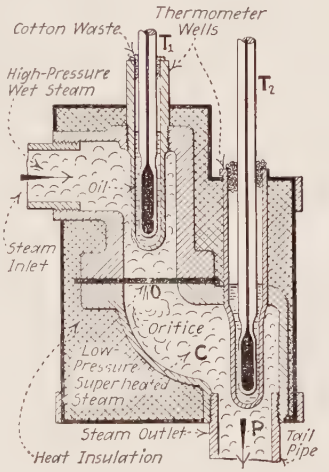

Fig. 351.—Section of Barrus throttling calorimeter in operation.

393. Table Showing Density and Specific Volume Of Water At Different Temperatures.—Abridged from "Steam Tables" by Marks and Davis (Longmans).

Temperature, deg. Fahr.	Specific volume, cu. ft. per lb.	Density, lb. per cu. ft.	Temperature, deg. Fahr.	Specific volume, cu. ft. per lb.	Density, lb. per cu. ft.
40	0.01602	62.43	210	0.01670	59.88
70	0.01605	62.30	250	0.01700	58 83
100	0.01613	62.00	300	0.01744	57.33
130	0.01625	61.55	350	0.01800	55.57
170	0.01645	60.80	400	0.0187	53.5

394. Table Giving The Properties Of 1 lb. Of Dry Saturated Steam. (Based on data by L. S. Marks and H. N. Davis, Longmans Green and Co.)

Pressure		Temperature, deg. Fahr.	Heat—British thermal units					Entropy (a ratio) B.t.u. per average abs. F. degree			Specific volume, cu. ft. per lb.	Density, lb. per cu. ft.
					Latent							
Inches of mercury abs.	Lb. per sq. in. abs.		Total of steam	Of liquid (water)	Total	Internal	External	Total	Of liquid	Of vaporization		
(1) P_M	(2) P	(3) T	(4) H_D	(5) h	(6) L	(7) L_I	(8) L_F	(9) n_D	(10) n_L	(11) n_V	(12) V_D	(13) D
0.1804	0.0886	32	1,073.4	0.0	1,073.4	1,019.3	54.1	2.1832	0.0000	2.1832	3,294.0	0.0003
0.502	0.2472	59	1,085.4	27.08	1.058.3	1,001.3	57.0	2.0944	0.0536	2.0408	1,249.2	0.0008
0.99	0.4893	79	1,094.3	47.04	1.047.3	988.1	59.2	2.0358	0.0913	1.9445	657.0	0.0015
1.50	0.741	92	1,100.1	60.0	1,040.0	979.4	60.6	2.0007	0.1151	1.8856	442.2	0.0023
1.98	0.975	101	1,104.0	68.97	1,035.1	973.5	61.6	1.9776	0.1313	1.8463	341.0	0.0029
2.51	1.235	109	1,107.5	76.94	1,030.6	968.2	62.4	1.9678	0.1454	1.8124	272.9	0.0037
2.98	1.467	115	1,110.2	82.92	1,027.2	964.2	63.0	1.9435	0.1559	1.7876	231.9	0.0043
3.52	1.736	121	1,112.8	88.91	1,023.9	960.2	63.7	1.9296	0.1662	1.7634	197.9	0.0051
4.04	1.992	126	1,115.0	93.90	1,021.1	956.8	64.3	1.9183	0.1747	1.7436	173.9	0.0058
4.50	2.219	130	1,116.7	97.89	1,018.8	954.1	65.1	1.9095	0.1816	1.7279	157.1	0.0064
5.01	2.467	134	1,118.4	101.88	1,016.5	951.4	65.1	1.9008	0.1883	1.7125	142.2	0.0070
	1	101.83	1,104.4	69.8	1,034.6	972.9	61.7	1.9754	0.1327	1.8427	333.0	0.0030
	2	126.15	1,115.0	91.6	1,021.0	956.7	64.3	1.9180	0.1719	1.7431	173.5	0.0058
	3	141.52	1,121.6	109.4	1,012.3	946.4	65.9	1.8848	0.2008	1.6840	118.5	0.0085
	4	153.01	1,126.5	120.9	1,005.7	938.6	67.1	1.8614	0.2198	1.6416	90.5	0.0111
	5	162.28	1,130.5	130.1	1,000.3	932.4	67.9	1.8432	0.2348	1.6084	73.33	0.0136
	6	170.06	1,133.7	137.9	995.8	927.0	68.8	1.8285	0.2471	1.5814	61.89	0.0162
	7	176.85	1,136.5	144.7	991.8	922.4	69.4	1.8161	0.2579	1.5582	53.56	0.0187
	8	182.86	1,139.0	150.8	998.2	918.2	70.0	1.8053	0.2673	1.5380	47.27	0.0212
	9	188.27	1,141.1	156.2	985.0	914.4	70.6	1.7958	0.2756	1.5202	42.36	0.0236
	10	193.22	1,143.1	161.1	982.0	910.9	71.1	1.7874	0.2832	1.5042	38.38	0.0261

Ld. per sq. in. gage P_G													
0	11	197.75	1,144.9	165.7	979.2	907.8	71.4	1.7797	0.2902	1.4895	35.10	0.0285
0.3	12	201.96	1,146.5	169.9	976.6	901.8	71.8	1.7727	0.2907	1.4760	32.36	0.0309
	13	205.87	1,148.0	173.8	974.2	902.0	72.2	1.7664	0.3025	1.4639	30.03	0.0333
	14	209.55	1,149.4	177.5	971.9	899.3	72.6	1.7604	0.3081	1.4523	28.02	0.0357
	15	213.0	1,150.7	181.0	969.7	896.6	72.9	1.7549	0.3133	1.4416	26.27	0.0381
0.3	16	216.3	1,152.0	184.4	967.6	894.4	73.2	1.7494	0.3183	1.4311	24.79	0.0404
1.3	17	219.4	1,153.1	187.5	965.6	892.1	73.5	1.7444	0.3229	1.4215	23.38	0.0423
2.3	18	222.4	1,154.2	190.5	963.7	889.9	73.8	1.7400	0.3273	1.4127	22.16	0.0451
3.3	19	225.2	1,155.2	193.4	961.8	887.8	74.0	1.7360	0.3315	1.4045	21.07	0.0475
4.3	20	228.0	1,156.2	196.1	960.0	885.8	74.2	1.7320	0.3355	1.3965	20.08	0.0498
5.3	21	230.6	1,157.1	198.8	958.3	883.9	74.4	1.7280	0.3393	1.3887	19.18	0.0521
6.3	22	233.1	1,158.0	201.3	956.7	882.0	74.7	1.7241	0.3430	1.3811	18.37	0.0545
7.3	23	235.5	1,158.8	203.8	955.1	880.2	74.9	1.7204	0.3465	1.3739	17.62	0.0568
8.3	24	237.8	1,159.6	206.1	953.5	878.5	75.0	1.7169	0.3499	1.3670	16.93	0.0591
9.3	25	240.1	1,160.4	208.4	952.0	876.8	75.2	1.7136	0.3532	1.3604	16.30	0.0614
10.3	26	242.2	1,161.2	210.6	950.6	875.1	75.5	1.7106	0.3564	1.3542	15.72	0.0636
11.3	27	244.4	1,161.9	212.7	949.2	873.5	75.7	1.7077	0.3594	1.3483	15.18	0.0659
12.3	28	246.4	1,162.6	214.8	947.8	872.0	75.8	1.7048	0.3623	1.3425	14.67	0.0682
13.3	29	248.4	1,163.2	216.8	946.4	870.5	75.9	1.7019	0.3652	1.3367	14.19	0.0705
14.3	30	250.3	1,163.9	218.8	945.1	869.0	76.1	1.6991	0.3680	1.3311	13.74	0.0728
15.3	32	254.1	1,165.1	222.6	942.5	866.2	76.3	1.6938	0.3733	1.3205	12.93	0.0773
17.3	34	257.6	1,166.3	226.2	940.1	863.4	76.7	1.6891	0.3784	1.3107	12.22	0.0818
19.3	36	261.0	1,167.3	229.6	937.7	860.8	76.9	1.6846	0.3832	1.3014	11.58	0.0863
21.3	38	264.2	1,168.4	232.9	935.5	858.3	77.2	1.6802	0.3877	1.2925	11.01	0.0908
23.3	40	267.3	1,169.4	236.1	933.3	855.9	77.4	1.6761	0.3920	1.2841	10.49	0.0953
25.3	42	270.2	1,170.3	239.1	931.2	853.6	77.6	1.6721	0.3962	1.2759	10.02	0.0998
27.3	44	273.1	1,171.2	242.0	929.2	851.3	77.9	1.6683	0.4002	1.2681	9.59	0.1043
29.3	46	275.8	1,172.0	244.8	927.2	849.2	78.0	1.6647	0.4040	1.2607	9.20	0.1087
31.3	48	278.5	1,172.8	247.5	925.3	847.1	78.2	1.6613	0.4077	1.2536	8.84	0.1131
33.3	50	281.0	1,173.6	250.1	923.5	845.0	78.5	1.6581	0.4113	1.2418	8.51	0.1175
35.3	52	283.5	1,174.3	252.6	921.7	843.1	78.6	1.6549	0.4147	1.2402	8.20	0.1219
37.3	54	285.9	1,175.0	255.1	919.9	841.1	78.8	1.6519	0.4180	1.2339	7.91	0.1263
39.3	56	288.2	1,175.7	257.5	918.2	839.3	78.9	1.6490	0.4212	1.2278	7.65	0.1307
41.3	58	290.5	1,176.4	259.8	916.5	837.4	79.1	1.6460	0.4242	1.2218	7.40	0.1350
43.3	60	292.7	1,177.0	262.1	914.9	835.6	79.3	1.6432	0.4272	1.2160	7.17	0.1394
45.3												

394. *Cont'd.* Table Giving the Properties of 1 lb. Of Dry Saturated Steam.

Pressure		Temperature, deg. Fahr.	Heat—British thermal units					Entropy (a ratio) B.t.u per average abs. F. degree			Specific volume, cu. ft. per lb.	Density, lb. per cu. ft.
Inches of mercury abs.	Lb. per sq. in. abs.		Total of steam	Of liquid (water)	Latent			Total	Of liquid	Of vaporization		
					Total	Internal	External					
(1) P_G	(2) P	(3) T	(4) H_D	(5) h	(6) L	(7) L_I	(8) L_E	(9) n_D	(10) n_L	(11)	(12) V_D	(13) D
47.3	62	294.9	1,177.6	264.3	913.3	833.9	79.4	1.6406	0.4302	1.2104	6.95	0.1438
49.3	64	297.0	1,178.2	266.4	911.8	832.2	79.6	1.6380	0.4330	1.2050	6.75	0.1482
51.3	66	299.0	1,178.8	268.5	910.2	830.5	79.7	1.6355	0.4358	1.2007	6.56	0.1525
53.3	68	301.0	1,179.3	270.6	908.7	828.9	79.8	1.6331	0.4385	1.1946	6.38	0.1569
55.3	70	302.9	1,179.8	272.6	907.2	827.3	79.9	1.6307	0.4411	1.1896	6.20	0.1612
57.3	72	304.8	1,180.4	274.5	905.8	825.8	80.0	1.6285	0.4437	1.1848	6.04	0.1656
59.3	74	306.7	1,180.9	276.5	904.4	824.2	80.2	1.6263	0.4462	1.1810	5.89	0.1699
61.3	76	308.5	1,181.4	278.3	903.0	822.7	80.3	1.6242	0.4487	1.1755	5.74	0.1743
63.3	78	310.3	1,181.8	280.2	901.7	821.3	80.4	1.6221	0.4511	1.1710	5.60	0.1786
65.3	80	312.0	1,182.3	282.0	900.3	819.8	80.5	1.6200	0.4535	1.1665	5.47	0.1829
67.3	82	313.8	1,182.8	283.8	899.0	818.4	80.6	1.6180	0.4557	1.1623	5.34	0.1873
69.3	84	315.4	1,183.2	285.5	897.7	817.0	80.7	1.6160	0.4579	1.1581	5.22	0.1915
71.3	86	317.1	1,183.6	287.2	896.4	815.6	80.8	1.6141	0.4601	1.1540	5.10	0.1959
73.3	88	318.7	1,184.0	288.9	895.2	814.3	80.9	1.6123	0.4623	1.1500	5.60	0.2001
75.3	90	320.3	1,184.4	290.5	893.9	813.0	80.9	1.6105	0.4644	1.1461	4.89	0.2044
77.3	92	321.8	1,184.8	292.1	892.7	811.7	81.0	1.6087	0.4664	1.1423	4.79	0.2087
79.3	94	323.4	1,185.2	293.7	891.5	810.4	81.1	1.6069	0.4684	1.1385	4.69	0.2130
81.3	96	324.9	1,185.6	295.3	890.3	809.1	81.2	1.6052	0.4704	1.1348	4.60	0.2172
83.3	98	326.4	1,186.0	296.8	889.2	807.9	81.3	1.6036	0.4724	1.1312	4.51	0.2215
85.3	100	327.8	1,186.3	298.3	888.0	806.6	81.4	1.6020	0.4743	1.1277	4.429	0.2258

90.3	105	331.4	1,187.2	302.0	885.2	803.6	81.6	1.5980	0.4789	1.1191	4.230	0.2365
95.3	110	334.8	1,188.0	305.5	882.5	800.7	81.8	1.5942	0.4834	1.1108	4.047	0.2472
100	115	338.1	1,188.8	309.0	879.8	797.9	81.9	1.5907	0.4877	1.1030	3.880	0.2577
105	120	341.3	1,189.6	312.3	877.2	795.2	82.0	1.5873	0.4919	1.0954	3.726	0 2683
110	125	344.4	1,190.3	315.5	874.7	792.6	82.1	1.5839	0.4959	1.0880	3.583	0.2991
115	130	347.4	1,191.0	318.6	872.3	790.0	82.3	1.5807	0.4998	1.0809	3.452	0.2997
120	135	350.3	1,191.6	321.7	869.9	787.5	82.4	1.5777	0.5035	1.0742	3.331	0.3002
125	140	353.1	1,192.2	324.6	867.6	785.0	82.6	1.5747	0.5072	1.0675	3.219	0.3107
130	145	355.8	1,192.8	327.4	865.4	782.7	82.7	1.5719	0.5107	1.0612	3.112	0.3213
135	150	358.5	1,193.4	330.2	863.2	780.4	82.8	1.5692	0.5142	1.0550	3.012	0.3320
140	155	361.0	1,194.0	332.9	861.0	778.1	82.9	1.5664	0.5175	1.0489	2.920	0.3425
145	160	363.6	1,194.5	335.6	858.8	775.8	83.0	1.5639	0.5208	1.0431	2.834	0.3529
150	165	366.0	1,195.0	338.2	856.8	773.6	83.2	1.5615	0.5239	1.0376	2.753	0.3633
155	170	368.5	1,195.4	340.7	854.7	771.5	83.2	1.5590	0.5269	1.0321	2.675	0.3738
160	175	370.8	1,195.9	343.2	852.7	769.4	83.3	1.5567	0.5299	1.0268	2.602	0.3843
165	180	373.1	1,196.4	345.6	850.8	767.4	83.4	1.5543	0.5328	1.0215	2.533	0.3948
170	185	375.4	1,196.8	348.0	848.8	765.4	83.4	1.5520	0.5356	1.0164	2.468	0.4052
175	190	377.6	1,197.3	350.4	846.9	763.4	83.5	1.5498	0.5384	1.0114	2.406	0.4157
180	195	379.8	1,197.7	352.7	845.0	761.4	83.6	1.5476	0.5410	1.0066	2.346	0.4262
185	200	381.9	1,198.1	354.9	843.2	759.5	83.7	1.5456	0.5437	1.0019	2.290	0.437
190	205	384.0	1,198.5	357.1	841.4	757.6	83.8	1.5436	0.5463	0.9973	2.237	0.447
195	210	386.0	1,198.8	359.2	839.6	755.8	83.8	1.5416	0.5488	0.9928	2.187	0.457
200	215	388.0	1,199.2	361.4	837.9	754.0	83.9	1.5398	0.5513	0.9885	2.138	0.468
205	220	389.9	1,199.6	363.4	836.2	752.3	83.9	1.5379	0.5538	0.9841	2.091	0.478
210	225	391.9	1,199.9	365.5	834.4	750.5	83.9	1.5361	0.5562	0.9799	2.046	0.489
215	230	393.8	1,200.2	367.5	832.8	748.8	84.0	1.5344	0.5586	0.9758	2.004	0.499
220	235	395.6	1,200.6	369.4	831.1	747.0	84.1	1.5327	0.5610	0.9717	1.964	0.509
225	240	397.4	1,200.9	371.4	829.5	745.4	84.1	1.5309	0.5633	0.9676	1.924	0.520
230	245	399.3	1,201.2	373.3	827.9	743.7	84.2	1.5293	0.5655	0.9638	1.887	0.530
235	250	401.1	1,201.5	375.2	826.3	742.0	84.3	1.5276	0.5676	0.960	1.850	0.541
255	270	409.7	1,202.6	382.5	820.1	735.8	84.3	1.5214	0.5760	0.9454	1.718	0.582
285	300	417.5	1,204.1	392.7	811.3	726.8	84.5	1.5129	0.5878	0.925	1.551	0.645
385	400	444.8	1,208.	422.	786.0	701.	85.	1.489	0.621	0.868	1.17	0.86
485	500	467.3	1,210.	448.	762.	678.	84.	1.470	0.648	0.822	0.93	1.08
...	1,000	544.8	1,200.	535.	665.	587.	78.	1.39	0.737	0.668	0.46	2.18
...	2,000	636.0			511.	444.	67.			0.446	0.21	4.9
Crit.	3,200	706.1			000.	000.	00.			0.000	0.05	20.1

395. Table Giving The Properties Of 1 lb. Of Superheated Steam (condensed from Marks and Davis' "Steam Tables and Diagrams").

Pressure, lb. per sq. in. abs.	Temp. of saturated steam, deg. Fahr	Property	Superheat, degrees Fahrenheit								
			20	40	60	80	100	150	200	250	300
		V_S	20.73	21.37	22.01	22.63	23.25	24.80	26.33	27.85	29.37
20	228.0	H_S	1,165.7	1,175.2	1,184.6	1,194.1	1,203.5	1,227.1	1,250.6	1,274.1	1,297.6
		n_S	1.7456	1.7587	1.7716	1.7840	1.7961	1.8251	1.8524	1.8781	1.9026
		V_S	10.83	11.16	11.50	11.82	12.13	12.93	13.70	14.48	15.25
40	267.3	H_S	1,179.3	1,189.1	1,198.9	1,208.7	1,218.4	1,242.4	1,266.4	1,290.3	1,314.1
		n_S	1.6895	1.7025	1.7151	1.7273	1.7392	1.7674	1.7940	1.8189	1.8427
		V_S	7.40	7.63	7.86	8.08	8.30	8.84	9.36	9.89	10.41
60	292.7	H_S	1,187.3	1,197.5	1,207.7	1,217.7	1,227.6	1,252.1	1,276.4	1,300.4	1,324.3
		n_S	1.6568	1.6698	1.6823	1.6944	1.7062	1.7342	1.7603	1.7849	1.8081
		V_S	5.65	5.83	6.00	6.18	6.34	6.75	7.17	7.56	7.95
80	312.0	H_S	1,193.0	1,203.6	1,214.0	1,224.2	1,234.3	1,259.0	1,283.6	1,307.8	1,331.9
		n_S	1.6338	1.6469	1.6594	1.6716	1.6833	1.7110	1.7368	1.7612	1.7840
		V_S	4.58	4.72	4.86	5.00	5.14	5.47	5.80	6.12	6.44
100	327.8	H_S	1,197.5	1,208.4	1,219.1	1,229.5	1,239.7	1,264.7	1,289.4	1,313.6	1,337.8
		n_S	1.6160	1.6294	1.6420	1.6541	1.6658	1.6933	1.7188	1.7428	1.7656
		V_S	3.85	3.98	4.10	4.22	4.33	4.62	4.89	5.17	5.44
120	341.3	H_S	1,201.1	1,212.4	1,223.3	1,233.8	1,244.1	1,269.3	1,294.1	1,318.4	1,342.7
		n_S	1.6016	1.6152	1.6279	1.6400	1.6517	1.6789	1.7041	1.7280	1.7505
		V_S	3.32	3.44	3.54	3.65	3.75	4.00	4.24	4.48	4.71
140	353.1	H_S	1,204.3	1,215.8	1,226.8	1,237.5	1,248.0	1,273.3	1,298.2	1,322.6	1,346.9
		n_S	1.5894	1.6031	1.6159	1.6280	1.6395	1.6666	1.6916	1.7152	1.7376

		V_S	2.93	3.03	3.12	3.21	3.30	3.53	3.74	3.95	4.15
160	363.6	H_S	1,207.0	1,218.8	1,230.0	1,240.8	1,251.3	1,276.8	1,310.7	1,326.2	1,350.6
		n_S	1.5789	1.5928	1.6056	1.6177	1.6292	1.6561	1.6810	1.7043	1.7266
		V_S	2.62	2.71	2.80	2.81	2.96	3.16	3.35	3.54	3.72
180	373.1	H_S	1,209.4	1,221.5	1,232.8	1,243.8	1,254.3	1,279.9	1,304.8	1,329.5	1,353.9
		n_S	1.5697	1.5838	1.5767	1.6088	1.6201	1.6468	1.6706	1.6948	1.7169
		V_S	2.37	2.45	2.53	2.61	2.68	2.86	3.04	3.21	3.38
200	381.9	H_S	1,211.6	1,223.9	1,235.5	1,246.5	1,257.1	1,282.6	1,307.7	1,332.4	1,357.0
		n_S	1.5614	1.5757	1.5886	1.6007	1.6120	1.6358	1.6632	1.6862	1.7082
		V_S	2.16	2.24	2.31	2.38	2.45	2.62	2.78	2.94	3.10
220	389.9	H_S	1,213.6	1,226.2	1,237.9	1,248.9	1,259.6	1,285.2	1,310.3	1,335.1	1,359.8
		n_S	1.5541	1.5686	1.5816	1.5936	1.6049	1.6312	1.6558	1.6787	1.7005
		V_S	1.99	2.06	2.13	2.20	2.26	2.42	2.57	2.71	2.85
240	397.4	H_S	1,215.4	1,228.3	1,240.1	1,251.3	1,261.9	1,287.6	1,312.8	1,337.6	1,362.3
		n_S	1.5476	1.5623	1.5753	1.5873	1.5985	1.6246	1.6492	1.6720	1.6937
		V_S	1.84	1.91	1.97	2.04	2.10	2.24	2.39	2.52	2.65
260	404.5	H_S	1,217.1	1,230.3	1,242.3	1,253.4	1,264.1	1,289.9	1,315.1	1,340.0	1,364.7
		n_S	1.5416	1.5564	1.5695	1.5815	1.5926	1.6186	1.6430	1.6658	1.6874
		V_S	1.72	1.78	1.84	1.90	1.95	2.09	2.22	2.35	2.98
280	411.2	H_S	1,218.7	1,232.2	1,244.3	1,255.5	1,266.2	1,291.9	1,317.2	1,342.2	1,367.0
		n_S	1.5362	1.5512	1.5643	1.5762	1.5873	1.6133	1.6375	1.6603	1.6818
		V_S	1.60	1.66	1.72	1.78	1.83	1.96	2.09	2.21	2.33
300	417.5	H_S	1,220.2	1,234.1	1,246.2	1,257.4	1,268.2	1,294.0	1,319.3	1,344.3	1,369.2
		n_S	1.5310	1.5462	1.5594	1.5713	1.5824	1.6082	1.6323	1.6550	1.6765

396. To Compute The Quality Of Steam From The Results Of The Throttling Calorimeter, use the following formula which is derived below:

$$x = \frac{1{,}050 + 0.46T_2 - h}{L} \quad \text{(decimal)} \tag{278}$$

Wherein: x = the quality of steam, expressed decimally. T_2 = the temperature shown by the thermometer T_2 (Fig. 350) in degrees Fahrenheit. h = the heat of liquid corresponding to the temperature of the steam, T_1, before passing through the orifice as shown by thermometer T_1 (Fig. 350), in British thermal units per pound. L = latent heat of steam corresponding to T_1, the same temperature as for h in British thermal units per pound.

EXAMPLE.—Suppose the temperature of the entering steam, T_1, is 355.8° F. and the temperature of the steam in the exhaust side of the calorimeter, T_2, is 250.3° F. The pressure in the calorimeter chamber, C, is assumed to be practically atmospheric. What is the quality of the steam? SOLUTION.—By For. 278, the quality, $x = (1{,}050 + 0.46T_2 - h)/L = (1{,}050 + 0.46 \times 250.3 - 327.4)/865.4 = 0.969$, or 96.9 *per cent.*

DERIVATION.—As the calorimeter is well insulated and there is a sufficient flow of steam so that the heat loss in it may be neglected, the total heat of the steam will be the same before and after passing through the orifice. If the temperature of the wet steam before passing through the orifice is T_1, the corresponding total heat of the wet steam (by For. 242) $= h + xL$. If the steam is superheated after passing through the orifice, the total heat of the superheated steam (by For. 244) $= H_D + CT_S$. Since the two are equal, $h + xL = H_D + CT_S$, and:

$$x = \frac{H_D + CT_S - h}{L} \quad \text{(decimal)} \tag{279}$$

Or:

$$x = \frac{H_D + C(T_2 - T_3) - h}{L} \quad \text{(decimal)} \tag{280}$$

Wherein: $T_S = T_2 - T_3$ or the difference between the observed temperature and the temperature corresponding, in a steam table, to the observed pressure after passing through the orifice. When a pressure corresponding to a temperature of about 213° F. is obtained on the atmospheric side of the orifice, the atmospheric values for H_D, C and T_3 may be substituted and For. (280) becomes:

$$x = \frac{1{,}150.7 + 0.46(T_2 - 213) - h}{L} \quad \text{(decimal)} \tag{281}$$

And simplifying:

$$x = \frac{1{,}050 + 0.46T_2 - h}{L} \quad \text{(decimal)} \tag{282}$$

Which is the same as For. (278).

397. When Steam Is Too Wet To Superheat In A Throttling Calorimeter (Sec. 395) its quality may ordinarily be measured in a *separating calorimeter* (Fig. 352). This is a device for mechanically separating and measuring the water suspended in the steam. The quality is found by dividing the weight of dry steam by the sum of the weight of the moisture and the

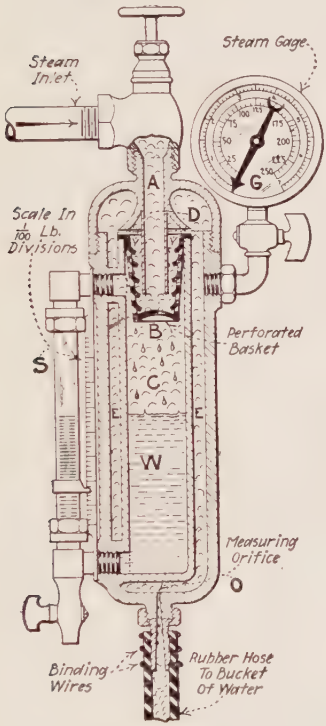

Fig. 352.—Separating calorimeter (which separates, mechanically, the water from the steam).

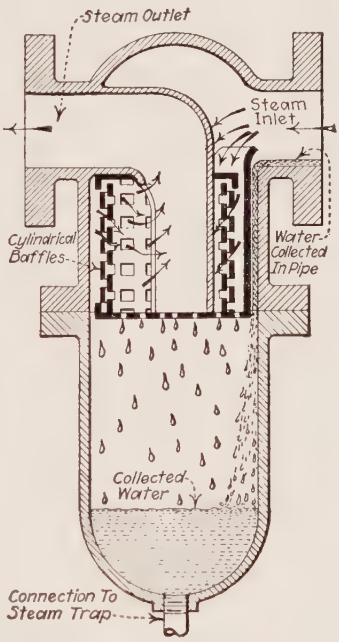

Fig. 353.—Steam separator for removing entrained moisture.

weight of the dry steam. It is impossible, however, to completely separate all of the liquid from the vapor with a separating calorimeter. Hence, such calorimeters always indicate a quality slightly in excess of the actual. When the steam pressure is less than about 50 lb. per sq. in., a separating calorimeter is very inaccurate. A throttling calorimeter may, however, be used on the discharge from the separating calori-

meter so as to correct the error. The operation of the separating calorimeter is explained below.

Explanation.—The steam enters the calorimeter through the tube, *A*, and discharges into the metal basket, *B*, which has perforations through its sides. The bottom of the basket is not perforated. Hence, to reach the outlet, *D*, above, the steam must make a sharp turn as it leaves the tube, *A*. In making this turn, the moisture in the steam, being heavier than the dry vapor, is thrown through the perforations in the side of *B* into the inner chamber, *C*, where it collects. The volume of the water, *W*, thus collected is read on the scale, *S*. The steam passes through, *D*, into the outer chamber, *E*, and then through the orifice, *O*, into the atmosphere or into a bucket of water. The rate of steam flow through the orifice, *O*, will depend on the pressure in *E*. The gage, *G*, has two sets of graduations, one showing the pressure in *E*, and the other showing the weight of steam flow through *O* during a 10-minute period. As this gage for the steam flow is unreliable, a better scheme is to obtain the weight of the steam by condensing it—by passing it into a bucket of water—and then weighing the condensed steam.

Note.—In Steam-engine Practice, Steam Is Usually Passed Through A Separator (Fig. 353) Before It Reaches The Engine. Hence its quality on entering the engine is high enough to be measured in a throttling calorimeter.

398. Ammonia, Carbon Dioxide, And Sulphur Dioxide Vapors Are Used In Refrigeration Practice.—Since in mechanical refrigeration temperatures below 32° F. are required, it is desirable to employ some vapor which has (at moderate pressures) a boiling temperature lower than 32° F. It is difficult to utilize water vapor for refrigeration purposes because water has a relatively high freezing point —it would be a solid at temperatures which must be used in refrigeration. Ammonia, carbon dioxide, and sulphur dioxide are the vapors which are generally employed. Ammonia is a very satisfactory refrigerant for ordinary refrigeration purposes because, at moderate pressures (130 200 lb. per sq. in.), it can readily be condensed with cooling water at temperatures of 50 to 80° F. Sulphur dioxide condenses at pressures of from 40 to 60 lb. per sq. in. even with relatively warm condensing water. Thus this fluid is used to advantage in the tropics. Carbon dioxide is best suited for low-temperature refrigeration, but it must have cool condensing water, for otherwise the efficiency is greatly impaired. Carbon dioxide must be raised to a pressure, of nearly 1,000 lb. per sq. in. before it can be condensed at 80° F.

399. Table Giving The Properties Of One Pound Of Saturated Sulphur-dioxide Vapor from Marks' "Mechanical Engineers' Handbook."

Temp., deg. Fahr.	Pressure, lb. per sq. in. abs.	Heat content—B.t.u. per lb.				Entropy		Specific volume of sat. vapor, cu. ft. per lb.
		Total of vapor	Of liquid	Latent heat		Of liquid	Of vaporization	
				Total	Internal			
(1) T	(2) P	(3) H_D	(4) h	(5) L	(6) L_I	(7) n_L	(8) n	(11) V_D
−15	6.86	160.52	−14.28	174.80	161.04	−0.0308	0.3935	10.910
−10	7.90	161.02	−12.85	173.87	160.00	−0.0274	0.3869	9.510
− 5	9.03	161.50	−11.39	172.89	158.90	−0.0240	0.3803	8.410
0	10.35	161.92	−9.007	171.83	157.70	−0.0208	0.3739	7.490
5	11.80	162.29	−8.388	170.68	156.43	−0.0176	0.3675	6.660
10	13.40	162.59	−6.842	169.43	154.95	−0.0141	0.3608	5.910
15	15.15	162.87	−5.321	168.19	153.59	−0.0110	0.3546	5.210
20	17.09	163.12	−3.780	166.90	152.26	−0.0079	0.3483	4.635
25	19.17	163.30	−2.212	165.51	150.84	−0.0046	0.3418	4.135
30	21.46	163.43	−0.622	164.05	149.36	−0.0012	0.3351	3.716
35	24.04	163.51	+0.968	162.54	147.75	+0.0020	0.3287	3.350
40	26.82	163.55	2.565	160.99	146.11	0.0051	0.3224	3.005
45	29.90	163.53	4.156	159.37	144.40	0.0083	0.3160	2.700
50	33.38	163.45	5.850	157.60	142.68	0.0117	0.3094	2.433
55	36.96	163.33	7.510	155.82	140.92	0.0150	0.3029	2.210
60	40.53	163.19	9.203	153.99	138.95	0.0182	0.2965	2.003
65	44.92	162.99	10.900	152.09	137.12	0.0215	0.2900	1.817
70	49.56	162.73	12.580	150.15	135.29	0.0248	0.2835	1.650
75	54.33	162.44	14.310	148.13	133.28	0.0280	0.2771	1.499
80	59.58	162.09	16.090	146.00	131.16	0.0312	0.2707	1.361
85	65.25	161.70	17.830	143.87	129.04	0.0345	0.2642	1.238
90	71.25	161.25	19.640	141.61	126.85	0.0377	0.2578	1.137
95	77.66	160.74	21.420	139.32	124.63	0.0410	0.2513	1.041
100	84.75	160.19	23.170	137.02	122.39	0.0443	0.2442	0.950

400. Table Giving The Properties Of One Pound Of Saturated Ammonia Vapor (Based on data by Goodenough and Mosher, from Marks' "Mechanical Engineers' Handbook").

Temp., deg. Fahr.	Pressure, lb. per sq. in. abs.	Heat content—B.t.u. per lb.					Entropy			Specific volume	
		Total of vapor	Of liquid	Latent			Total	Of liquid	Of vaporization	Of liquid, cu. ft. per lb.	Of sat. vapor, cu. ft. per lb.
				Total	Internal	External					
(1) T	(2) P	(3) H_D	(4) h	(5) L	(6) L_I	(7) L_E	(8) n_D	(9) n_L	(10) n_V	(11) V_L	(12) V_D
−40	10.12	526.6	−75.3	601.9	554.2	47.7	1.2690	−0.1653	1.4343	0.0234	25.45
−35	11.74	528.2	−70.2	598.3	550.2	48.1	1.2551	−0.1531	1.4090	0.0235	22.14
−30	13.56	529.8	−65.0	594.7	546.2	48.5	1.2432	−0.1410	1.3842	0.0236	19.35
−25	15.61	531.3	−59.8	591.1	542.1	49.0	1.2308	−0.1290	1.3598	0.0238	16.95
−20	17.91	532.8	−54.6	587.4	538.0	49.4	1.2189	−0.1171	1.3360	0.0239	14.89
−15	20.46	534.3	−49.4	583.6	533.9	49.7	1.2072	−0.1054	1.3126	0.0240	13.15
−10	23.30	535.7	−44.2	579.9	529.8	50.1	1.1958	−0.0938	1.2896	0.0241	11.63
−05	26.46	537.1	−38.9	576.1	525.6	50.5	1.1847	−0.0824	1.2671	0.0242	10.32
0	29.95	538.5	−33.7	572.2	521.4	50.8	1.1740	−0.0709	1.2449	0.0244	9.19
5	33.79	539.9	−28.4	568.3	517.1	51.2	1.1636	−0.0595	1.2231	0.0245	8.20
10	38.02	541.2	−23.2	564.4	512.9	51.5	1.1534	−0.0483	1.2017	0.0246	7.34
15	42.67	542.5	−17.9	560.4	508.6	51.8	1.1434	−0.0372	1.1806	0.0248	6.583

20	47.75	543.7	−12.6	556.3	504.2	52.1	1.1337	−0.0262	1.1599	0.0249	5.920
25	53.30	545.0	−7.3	552.2	499.8	52.4	1.1242	−0.0153	1.1395	0.0250	5.336
30	59.39	546.2	−1.9	548.1	495.4	52.7	1.1150	−0.0044	1.1194	0.0252	4.820
35	65.91	547.4	+3.5	543.9	491.0	52.9	1.1061	+0.0065	1.0996	0.0253	4.364
40	73.03	548.5	8.9	539.7	486.5	53.2	1.0974	0.0173	1.0801	0.0255	3.959
45	80.75	549.7	14.3	535.3	481.9	53.4	1.0889	0.0280	1.0609	0.0256	3.599
50	89.09	550.8	19.8	531.0	477.3	53.7	1.0806	0.0387	1.0419	0.0258	3.278
55	98.03	551.9	25.3	526.5	472.7	53.8	1.0725	0.0494	1.0231	0.0259	2.992
60	107.7	552.9	30.9	522.0	468.0	54.0	1.0647	0.0601	1.0046	0.0261	2.734
65	118.1	554.0	36.5	517.5	463.3	54.2	1.0571	0.0708	0.9863	0.0263	2.503
70	129.2	555.0	42.1	512.8	458.5	54.3	1.0496	0.0813	0.9683	0.0264	2.296
75	141.1	556.0	47.8	508.1	453.7	54.4	1.0423	0.0919	0.9504	0.0266	2.109
80	153.9	557.0	53.6	503.4	448.8	54.6	1.0333	0.1025	0.9328	0.0268	1.940
85	167.4	557.9	59.4	498.5	443.9	54.6	1.0285	0.1132	0.9153	0.0270	1.788
90	181.8	558.9	65.3	493.5	438.9	54.6	1.0218	0.1238	0.8980	0.0271	1.650
95	197.3	559.8	71.3	488.5	433.9	54.6	1.0152	0.1344	0.8808	0.0273	1.524
100	213.8	560.7	77.3	483.4	428.7	54.7	1.0088	0.1450	0.8638	0.0275	1.408
105	231.2	561.6	83.4	478.2	423.5	54.7	1.0026	0.1557	0.8469	0.0277	1.305
110	249.6	562.5	89.6	472.9	418.3	54.6	0.9966	0.1664	0.8302	0.0280	1.210
115	269.2	563.3	95.9	467.4	412.9	54.5	0.9907	0.1722	0.8135	0.0282	1.122
120	289.9	564.2	102.2	461.9	407.5	54.4	0.9850	0.1881	0.7969	0.0284	1.042
125	311.6	565.0	108.7	456.3	402.0	54.3	0.9795	0.1990	0.7805	0.0286	0.970

401. Table Giving The Properties Of One Pound Of Saturated Carbon-dioxide Vapor (from Marks' "MECHANICAL ENGINEERS' HANDBOOK").

Temp., deg. Fahr.	Pressure, lb. per sq. in. abs.	Heat content—B.t.u. per lb.				Entropy		Specific volume	
		Total of vapor	Of liquid	Latent		Of liquid	Of vaporization	Of liquid, cu. ft. per lb.	Of vayor, cu. ft. per lb.
				Total	Internal				
(1) T	(2) P	(3) H_D	(4) h	(5) L	(6) L_I	(7) n_L	(8) n_V	(9) V_L	(10) V_D
−25	203 4	100.22	−26.91	127.13	110.8	−0.0561	0.2925	0.01551	0.4575
−20	221.0	100.50	−24.75	125.25	109.0	−0.0513	0.2851	0.01556	0.4173
−15	240.5	100.74	−22.72	123.46	107.3	−0.0467	0.2778	0.01565	0.3810
−10	261.8	100.88	−20.56	121.44	105.4	−0.0419	0.2702	0.01578	0.3481
− 5	284.1	100.99	−18.31	119.30	103.4	−0.0372	0.2626	0.01594	0.3185
0	308.0	101.00	−16.00	117.00	101.3	−0.0325	0.2549	0.01612	0.2918
5	334.2	100.97	−13.73	114.70	99.2	−0.0276	0.2470	0.01631	0.2672
10	362.5	100.89	−11.36	112.35	96.9	−0.0227	0.2391	0.01652	0.2450
15	391.0	100.70	− 8.94	109.64	94.3	−0.0176	0.2309	0.01675	0.2244
20	421.6	100.43	− 6.40	106.83	91.8	−0.0126	0.2228	0.01696	0.2060
25	454.7	100.08	− 3.74	102.82	88.4	−0.0074	0.2143	0.01720	0.1882
30	488.8	99.43	− 1.04	100.47	86.7	−0.0021	0.2014	0.01747	0.1724
35	525.5	99.00	+ 1.74	97.26	83.6	+0.0032	0.1968	0.01776	0.1580
40	546.5	98.25	4.36	93.89	80.4	0.0087	0.1876	0.01805	0.1444
45	606.0	97.32	7.54	89.78	77.05	0.0145	0.1780	0.01835	0.1323
50	650.0	96.30	10.76	85.54	73.31	0.0205	0.1679	0.01870	0.1205
55	696.0	95.00	14.18	80.82	69.16	0.0268	0.1572	0.01918	0.1090
60	744.0	93.54	17.85	75.69	64.90	0.0334	0.1461	0.01986	0.0986
65	794.0	91.67	21.50	70.17	60.08	0.0406	0.1334	0.02052	0.0890
70	847.0	89.35	26.02	63.33	54.03	0.0483	0.1201	0.02136	0.0816
75	906.0	86.36	30.96	55.40	47.20	0.0576	0.1037	0.02230	0.0706
80	965.0	82.80	36.80	46.00	39.16	0.0684	0.0843	0.02365	0.0614
85	1,026.0	76.60	44.67	30.23	26.80	0.0828	0.0559	0.02620	0.0500
87	1,052.0	71.80	48.98	23.82	18.25	0.0923	0.0393	0.02782	0.0440
88.43	1,071.0	61.45	61.45	0.00	0.00	0.1120	0.000	0.0346	0.0346

QUESTIONS ON DIVISION 11

1. What is the distinction between a vapor and a gas? Do gases and vapors behave similarly?

2. What are the three conditions in which a vapor may exist? Define each in two ways. Which one seldom occurs in practice?

3. What are the two forms of saturated vapor? Define each.

4. How is the amount of superheat in a vapor expressed?

5. How may the condition of a vapor be determined?

6. What is meant by the quality of a vapor?

7. How may the properties of a vapor at some pressure between those given in the table be found?

8. Define heat of the liquid. Total heat of a vapor. Of what values given in the vapor tables is the *total heat* the sum?

9. How may the *total heat* of a wet vapor be found? Of a superheated vapor?

10. Define the *specific volume* of a vapor. How is it determined for wet, dry saturated, and for superheated vapors?

11. How would you find the quality of a wet vapor if you knew only its pressure and specific volume?

12. Give the general formula for finding the internal heat energy in any vaporous substance. What is the starting point from which internal energy is measured?

13. Of what two factors may heat energy be considered the product? Explain the similarity, on this basis, of heat and other forms of energy.

14. Give two definitions of *entropy*. Can a substance suffer an increase or decrease of heat content without suffering a change in entropy? Explain.

15. Can entropy be measured? How are entropy values determined? Do all substances have entropy? Explain.

16. Of what use is entropy in heat calculations? Of what value are charts which employ entropy?

17. Is it possible to determine the absolute entropy of the substance? Why?

18. Do we ever need to know the absolute entropy of a substance? From what starting point is entropy generally measured?

19. What is the difference between absolute entropy and total entropy?

20. How can the change in entropy during heat transfer be determined? Explain fully.

21. Explain the usefulness of the temperature-entropy diagram for any process.

22. What sort of temperature-entropy diagrams are useful in engineering? What is the difference between such a *diagram* and a *chart*?

23. How would you find the entropy of a dry saturated vapor? Of a superheated vapor? Of a wet vapor?

24. What is a *Mollier diagram*? Using values from the steam tables show by a sketch how a Mollier diagram is constructed. Indicate on your sketch what portion of the diagram is generally most used.

25. In how many ways may vapors expand and be compressed? What may be considered as the fundamental expansion or compression processes?

26. What are the three principal kinds of vapor expansions which are encountered in actual machines?

27. What is an *isentropic expansion*? In what kind of machines do nearly isentropic expansions occur? Why is the isentropic expansion considered as the ideal? Explain with a sketch.

28. What changes in quality or superheat accompany isentropic expansions of vapors? How would you determine the quality or superheat of a vapor after isentropic expansion?

29. Where do constant-pressure expansions of vapor occur in practical machines?

30. Under what conditions does a vapor expand without change of heat content? In what practical processes do such expansions occur?

31. What are the three principal ways in which vapors may be compressed? Which of these is not practically attainable? In what machines and under what conditions are these compressions obtained?

32. Derive the energy relations for an isentropic process for a vapor. What quantity can be read directly from a heat-entropy chart?

33. State and derive the energy relations for a constant-pressure process for a vapor.

34. What are the energy relations for throttling and isodynamic processes?

35. What characteristics of steam make it so suitable a medium for heat engines?

36. Make a sketch of and explain the principle of operation of the throttling calorimeter.

37. When cannot a throttling calorimeter be used? What calorimeter is then used and how does it operate? Make a sketch of it. Is this calorimeter very accurate?

38. Under what different conditions of refrigeration are ammonia, sulphur dioxide, and carbon dioxide used? Which of these is most generally used?

PROBLEMS ON DIVISION 11

1. What is the total heat given off in the condensation of 1,500 lb. of wet steam at 20 lb. per sq. in. abs. having a quality of 92.8 per cent. when the condensate is cooled to 60° F.?

2. What amount of heat must be supplied to 1,720 lb. of water at 49° F. to convert it to steam at 185 lb. per sq. in. gage pressure and 432° F.?

3. Steam at 140 lb. per sq. in. abs. and 98 per cent. quality expands in a turbine to a pressure of 2 lb. per sq. in. abs. After this expansion it has a quality of 81 per cent. By calculations from the values given in the Steam Table, find the heat absorbed by the turbine from 1 lb. of steam. Note: Heat absorbed equals heat content of steam at throttle minus the heat content of exhaust steam.

4. Find the specific volume of the steam entering and leaving the turbine of Prob. 3.

5. Find the internal energy of the steam entering and leaving the turbine of Prob. 3.

6. Find, without the use of the chart (Fig. 343), the increase in entropy during the expansion in Prob. 3. How much more heat is in 1 lb. of the exhaust steam than would have been in it, had the steam expanded isentropically?

7. Steam at 160 lb. per sq. in. abs. and 40° F. superheat expands isentropically (that is, along a constant entropy line) to a pressure of 5 lb. per sq. in. abs. By means of the chart find the quality of the steam after this expansion? Find the quality of the steam after expansion by calculation from the entropy values given in the steam tables without using the chart, and check this value with that found by means of the chart.

8. How much external work would be done by each pound of steam during its expansion in a steam-engine cylinder if the steam expanded isentropically from 200 lb. pre sq. in. abs. and 100° F. superheat to a pressure of 3 lb. per sq. in. abs.?

9. In the coils of an ammonia refrigerating system, vapor ammonia of 10 per cent quality and at $-10°$ F. is evaporated at constant pressure until its quality becomes 0.95, How much heat is absorbed by each pound of ammonia and how much external work is done during the process?

10. A throttling steam calorimeter gives readings as follows: Temperature before passing through orifice, 346° F. Temperature after passing through orifice, 256° F Pressure after passing through the orifice, 15 lb. per sq. in. abs. What is the quality of the entering steam?

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